

# 1 RESONANT OPTICAL MODULATORS

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## 4 RELATED APPLICATIONS

5 [0001] This application claims priority based on prior-filed co-pending U.S. provisional App.  
6 No. 60/257,248 entitled "Modulators for resonant optical power control devices and methods of  
7 fabrication and use thereof", filed 12/21/2000 in the name of Oskar J. Painter, Peter C. Sercel,  
8 Kerry J. Vahala, and Guido Hunziker, said provisional application being hereby incorporated by  
9 reference as if fully set forth herein. This application claims priority based on prior-filed co-  
10 pending U.S. provisional App. No. 60/257,218 entitled "Waveguides and resonators for  
11 integrated optical devices and methods of fabrication and use thereof", filed 12/21/2000 in the  
12 name of Oskar J. Painter, said application being hereby incorporated by reference as if fully set  
13 forth herein.

## 14 GOVERNMENT RIGHTS

15 [0002] The U.S. Government may have limited rights in this application pursuant to Office of  
16 Naval Research Contract No. N00014-00-1-0072 via California Institute of Technology  
17 Subcontract No. 1008921. The U.S. Government may have limited rights in this application  
18 pursuant to DARPA Contract No. N00014-00-3-0023.

## 19 FIELD OF THE INVENTION

20 [0003] The field of the present invention relates to optical fiber communications. In particular,  
21 novel optical components, and methods of fabrication and use thereof, are described herein for  
22 modulating, switching, routing, and otherwise controlling optical signals in a wavelength  
23 specific manner.

## 24 BACKGROUND

25 [0004] This application is related to subject matter disclosed in:

26 [0005] A1) U.S. provisional Application No. 60/111,484 entitled "An all-fiber-optic  
27 modulator" filed 12/07/1998 in the names of Kerry J. Vahala and Amnon Yariv, said provisional  
28 application being hereby incorporated by reference in its entirety as if fully set forth herein;

- 1 [0006] A2) U.S. Application No. 09/454,719 entitled "Resonant optical wave power control  
2 devices and methods" filed 12/07/1999 in the names of Kerry J. Vahala and Amnon Yariv, said  
3 application being hereby incorporated by reference in its entirety as if fully set forth herein;
- 4 [0007] A3) U.S. provisional Application No. 60/108,358 entitled "Dual tapered fiber-  
5 microsphere coupler" filed 11/13/1998 in the names of Kerry J. Vahala and Ming Cai, said  
6 provisional application being hereby incorporated by reference in its entirety as if fully set forth  
7 herein;
- 8 [0008] A4) U.S. Application No. 09/440,311 entitled "Resonator fiber bi-directional coupler"  
9 filed 11/12/1999 in the names of Kerry J. Vahala, Ming Cai, and Guido Hunziker, said  
10 application being hereby incorporated by reference in its entirety as if fully set forth herein;
- 11 [0009] A5) U.S. provisional Application No. 60/183,499 entitled "Resonant optical power  
12 control devices and methods of fabrication thereof" filed 02/17/2000 in the names of Peter C.  
13 Sercel and Kerry J. Vahala, said provisional application being hereby incorporated by reference  
14 in its entirety as if fully set forth herein;
- 15 [0010] A6) U.S. provisional Application No. 60/226,147 entitled "Fiber-optic waveguides for  
16 evanescent optical coupling and methods of fabrication and use thereof", filed 08/18/2000 in the  
17 names of Peter C. Sercel, Guido Hunziker, and Robert B. Lee, said provisional application being  
18 hereby incorporated by reference in its entirety as if fully set forth herein;
- 19 [0011] A7) U.S. provisional Application No. 60/170,074 entitled "Optical routing/switching  
20 based on control of waveguide-ring resonator coupling", filed 12/09/1999 in the name of Amnon  
21 Yariv, said provisional application being hereby incorporated by reference in its entirety as if  
22 fully set forth herein;
- 23 [0012] A8) U. S. Pat. No. 6,052,495 entitled "Resonator modulators and wavelength routing  
24 switches" issued 04/18/2000 in the names of Brent E. Little, James S. Foresi, and Hermann A.  
25 Haus, said patent being hereby incorporated by reference in its entirety as if fully set forth  
26 herein;
- 27 [0013] A9) U. S. Pat. No. 6,101,300 entitled "High efficiency channel drop filter with  
28 absorption induced on/off switching and modulation" issued 08/08/2000 in the names of Shanhui

1 Fan, Pierre R. Villeneuve, John D. Joannopoulos, Brent E. Little, and Hermann A. Haus, said  
2 patent being hereby incorporated by reference in its entirety as if fully set forth herein;

3 [0014] A10) U. S. Pat. No. 5,926,496 entitled “Semiconductor micro-resonator device” issued  
4 07/20/1999 in the names of Seng-Tiong Ho and Deanna Rafizadeh, said patent being hereby  
5 incorporated by reference in its entirety as if fully set forth herein;

6 [0015] A11) U. S. Pat. No. 6,009,115 entitled “Semiconductor micro-resonator device” issued  
7 12/28/1999 in the name of Seng-Tiong Ho, said patent being hereby incorporated by reference in  
8 its entirety as if fully set forth herein;

9 [0016] A12) U.S. provisional Application No. 60/257,218 entitled “Waveguides and resonators  
10 for integrated optical devices and methods of fabrication and use thereof”, filed 12/21/2000 in  
11 the name of Oskar J. Painter, said provisional application being hereby incorporated by reference  
12 in its entirety as if fully set forth herein;

13 [0017] A13) U.S. provisional Application No. 60/257,248 entitled “Modulators for resonant  
14 optical power control devices and methods of fabrication and use thereof”, filed 12/21/2000 in  
15 the names of Oskar J. Painter, Kerry J. Vahala, Peter C. Sercel, and Guido Hunziker, said  
16 provisional application being hereby incorporated by reference in its entirety as if fully set forth  
17 herein;

18 [0018] A14) U.S. provisional Application No. 60/301,519 entitled “Waveguide-fiber Mach-  
19 Zender interferometer and methods of fabrication and use thereof”, filed 06/27/2001 in the  
20 names of Oskar J. Painter, David W. Verwooy, and Kerry J. Vahala, said provisional application  
21 being hereby incorporated by reference in its entirety as if fully set forth herein;

22 [0019] A15) U.S. non-provisional Application No. 09/788,303 entitled “Cylindrical processing  
23 of optical media”, filed 02/16/2001 in the names of Peter C. Sercel, Kerry J. Vahala, David W.  
24 Verwooy, and Guido Hunziker, said non-provisional application being hereby incorporated by  
25 reference in its entirety as if fully set forth herein;

26 [0020] A16) U.S. non-provisional Application No. 09/788,331 entitled “Fiber-ring optical  
27 resonators”, filed 02/16/2001 in the names of Peter C. Sercel, Kerry J. Vahala, David W.  
28 Verwooy, Guido Hunziker, and Robert B. Lee, said non-provisional application being hereby  
29 incorporated by reference in its entirety as if fully set forth herein;

1 [0021] A17) U.S. non-provisional Application No. 09/788,300 entitled “Resonant optical  
2 filters”, filed 02/16/2001 in the names of Kerry J. Vahala, Peter C. Sercel, David W. Vernooy,  
3 Oskar J. Painter, and Guido Hunziker, said non-provisional application being hereby  
4 incorporated by reference in its entirety as if fully set forth herein;

5 [0022] A18) U.S. non-provisional Application No. 09/788,301 entitled “Resonant optical  
6 power control device assemblies”, filed 02/16/2001 in the names of Peter C. Sercel, Kerry J.  
7 Vahala, David W. Vernooy, Guido Hunziker, Robert B. Lee, and Oskar J. Painter, said non-  
8 provisional application being hereby incorporated by reference in its entirety as if fully set forth  
9 herein;

10 [0023] A19) U.S. provisional Application No. 60/333,236 entitled “Alignment apparatus and  
11 methods for transverse optical coupling”, Docket No. CQC16P, filed 11/23/2001 in the names of  
12 Charles I. Grosjean, Guido Hunziker, Paul M. Bridger, and Oskar J. Painter, said provisional  
13 application being hereby incorporated by reference in its entirety as if fully set forth herein;

14 [0024] A20) U.S. non-provisional Application No. \_\_\_\_ / \_\_\_\_ , \_\_\_\_ entitled “Multi-layer  
15 dispersion-engineered waveguides and resonators”, Docket No. CQC14NP, filed concurrently  
16 with the present application in the names of Oskar J. Painter, David W. Vernooy, and Kerry J.  
17 Vahala, said non-provisional application being hereby incorporated by reference in its entirety as  
18 if fully set forth herein.

19 [0025] This application is also related to subject matter disclosed in the following publications,  
20 each of said publications being hereby incorporated by reference in its entirety as if fully set  
21 forth herein:

22 [0026] P1) Ming Cai, Guido Hunziker, and Kerry Vahala, “Fiber-optic add-drop device  
23 based on a silica microsphere whispering gallery mode system”, IEEE Photonics Technology  
24 Letters Vol. 11 686 (1999);

25 [0027] P2) J. C. Knight, G. Cheung, F. Jacques, and T. A. Birks, “Phased-matched excitation  
26 of whispering gallery-mode resonances by a fiber taper”, Optics Letters Vol. 22 1129 (1997);

27 [0028] P3) R. D. Pechstedt, P. St. J. Russell, T. A. Birks, and F. D. Lloyd-Lucas, “Selective  
28 coupling of fiber modes with use of surface-guided Bloch modes supported by dielectric  
29 multilayer stacks”, J. Opt. Soc. Am. A Vol. 12(12) 2655 (1995);

- 1 [0029] P4) R. D. Pechstedt, P. St. J. Russell, "Narrow-band in-line fiber filter using surface-  
2 guided Bloch modes supported by dielectric multilayer stacks", J. Lightwave Tech. Vol. 14(6)  
3 1541 (1996);
- 4 [0030] P5) Hiroshi Wada, Takeshi Kamijoh, and Yoh Ogawa, "Direct bonding of InP to  
5 different materials for optical devices", Proceedings of the third international symposium on  
6 semiconductor wafer bonding: Physics and applications, Electrochemical Society Proceedings,  
7 Princeton NJ, Vol. 95-7, 579 –591 (1995);
- 8 [0031] P6) R. H. Horng, D. S. Wuu, S.C. Wei, M. F. Huang, K.H. Chang, P.H. Liu, and K. C.  
9 Lin, "AlGaInP/AuBe/glass light emitting diodes fabricated by wafer-bonding technology", Appl.  
10 Phys. Letts. Vol. 75(2) 154 (1999);
- 11 [0032] P7) Y. Shi, C. Zheng, H. Zhang, J.H. Bechtel, L.R. Dalton, B.B. Robinson, W. Steier,  
12 "Low (sub-1-volt) halfwave voltage polymeric electro-optic modulators achieved by controlling  
13 chromophore shape", Science Vol. 288, 119 (2000);
- 14 [0033] P8) E. L. Wooten, K.M. Kiss, and A. Yi-Yan, "A review of lithium niobate  
15 modulators for fiber-optic communications systems", IEEE J. Selected Topics in Quantum  
16 Electronics, Vol. 6(1), 69 (2000);
- 17 [0034] P9) D.L. Huffaker, H. Deng, Q. Deng, and D.G. Deppe, "Ring and stripe oxide-  
18 confined vertical-cavity surface-emitting lasers", Appl. Phys. Lett., Vol. 69(23), 3477 (1996);
- 19 [0035] P10) Serpenguzel, S. Arnold, and G. Griffel, "Excitation of resonances of microspheres  
20 on an optical fiber", Opt. Lett. Vol. 20, 654 (1995);
- 21 [0036] P11) F. Treussart, N. Dubreil, J. C. Knight, V. Sandoghar, J. Hare, V. Lefevre-Seguin,  
22 J. M. Raimond, and S. Haroche, "Microlasers based on silica microspheres", Ann. Telecommun.  
23 Vol. 52, 557 (1997);
- 24 [0037] P12) M. L. Gorodetsky, A. A. Savchenkov, V. S. Ilchenko, "Ultimate Q of optical  
25 microsphere resonators", Optics Letters, Vol. 21, 453 (1996);
- 26 [0038] P13) Carl Arft, Diego R. Yankelovich, Andre Knoesen, Erji Mao, and James S. Harris  
27 Jr., "In-line fiber evanescent field electrooptic modulators", Journal of Nonlinear Optical  
28 Physics and Materials Vol. 9(1) 79 (2000);

- 1 [0039] P14) Pochi Yeh, Amnon Yariv, and Chi-Shain Hong, "Electromagnetic propagation in  
2 periodic stratified media. I. General theory", J. Optical Soc. Am., Vol. 67(4) 423 (1977);  
3 [0040] P15) Ming Cai, Oskar Painter, and Kerry J. Vahala, "Observation of critical coupling  
4 in a fiber taper to a silica-microsphere whispering-gallery mode system", Physical Review  
5 Letters, Vol. 85(1) 74 (2000);  
6 [0041] P16) M. Kondow, T. Kitatani, S. Nakatsuka, M. C. Larson, K. Nakahara, Y. Yazawa,  
7 M. Okai, and K. Uomi, "GaInNAs: A novel material for long-wavelength semiconductor  
8 lasers", IEEE Journal of Selected Topics in Quantum Electronics, Vol 3(3), 719 (1997);  
9 [0042] P17) H. Saito, T. Makimoto, and N. Kobayashi, "MOVPE growth of strained  
10 InGaAsN/GaAs quantum wells", J. Crystal Growth, Vol. 195 416 (1998);  
11 [0043] P18) W.G. Bi and C.W. Tu, "Bowing parameter of the band-gap energy of  $\text{GaN}_x\text{As}_{1-x}$ ",  
12 Appl. Phys. Lett. Vol. 70(12) 1608 (1997);  
13 [0044] P19) H. P. Xin and C. W. Tu, "GaInNAs/GaAs multiple quantum wells grown by gas-  
14 source molecular beam epitaxy", Appl. Phys Lett. Vol. 72(19) 2442 (1998);  
15 [0045] P20) B. Koley, F. G. Johnson, O. King, S. S. Saini, and M. Dagenais, "A method of  
16 highly efficient hydrolization oxidation of III-V semiconductor lattice matched to indium  
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18 [0046] P21) Z. J. Wang, S.-J. Chua, F. Zhou, W. Wang, and R. H. Wu, "Buried  
19 heterostructures InGaAsP/InP strain-compensated multiple quantum well laser with a native-  
20 oxidized InAlAs current blocking layer", Appl. Phys. Lett. Vol 73(26) 3803 (1998);  
21 [0047] P22) N. Ohnoki, F. Koyama, and K. Iga, "Superlattice AlAs/AlInAs-oxide current  
22 aperture for long wavelength InP-based vertical-cavity surface-emitting laser structure", Appl.  
23 Phys. Lett. Vol. 73(22) 3262 (1998);  
24 [0048] P23) N. Ohnoki, F. Koyama, and K. Iga, "Super-lattice AlAs/AlInAs for lateral-oxide  
25 current confinement in InP-based lasers", J. Crystal Growth Vol. 195 603 (1998);  
26 [0049] P24) K. D. Choquette, K. M. Geib, C. I. H. Ashby, R. D. Twesten, O. Blum, H. Q.  
27 Hou, D. M. Follstaedt, B. E. Hammons, D. Mathes, and R. Hull, "Advances in selective wet

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2 3(3) 916 (1997);  
3 [0050] P25) M. H. MacDougal, P. D. Dapkus, “Wavelength shift of selectively oxidized  
4 Al<sub>x</sub>O<sub>y</sub>-AlGaAs-GaAs distributed Bragg reflectors”, IEEE Photonics Tech. Lett. Vol. 9(7) 884  
5 (1997);  
6 [0051] P26) C. I. H. Ashby, M. M. Bridges, A. A. Allerman, B. E. Hammons, “Origin of the  
7 time dependence of wet oxidation of AlGaAs”, Appl. Phys. Lett. Vol. 75(1) 73 (1999);  
8 [0052] P27) P. Chavarkar, L. Zhao, S. Keller, A. Fisher, C. Zheng, J. S. Speck, and U. K.  
9 Mishra, “Strain relaxation of In<sub>x</sub>Ga<sub>1-x</sub>As during lateral oxidation of underlying AlAs layers”,  
10 Appl. Phys. Lett. Vol. 75(15) 2253 (1999);  
11 [0053] P28) R. L. Naone and L. A. Coldren, “Surface energy model for the thickness  
12 dependence of the lateral oxidation of AlAs”, J. Appl. Phys. Vol. 82(5) 2277 (1997);  
13 [0054] P29) M. H. MacDougalP. D. Dapkus, A. E. Bond, C.-K. Lin, and J. Geske, “Design  
14 and fabrication of VCSEL’s with Al<sub>x</sub>O<sub>y</sub>-GaAs DBR’s”, IEEE Journal of Selected Topics in  
15 Quantum Electronics Vol. 3(3) 905 (1997);  
16 [0055] P30) E. I. Chen, N. Holonyak, Jr., andM. J. Ries, “Planar disorder- and native-oxide-  
17 defined photopumped AlAs-GaAs superlattice minidisk lasers”, J. Appl. Phys. Vol. 79(11)  
18 8204 (1996); and  
19 [0056] P31) Y. Luo, D. C. Hall, L. Kou, L. Steingart, J. H. Jackson, O. Blum, and H. Hou,  
20 “Oxidized Al<sub>x</sub>Ga<sub>1-x</sub>As heterostructures planar waveguides”, Appl. Phys. Lett. Vol. 75(20) 3078  
21 (1999).  
22 [0057] Optical fiber and propagation of high-data-rate optical pulse trains therethrough has  
23 become the technology of choice for high speed telecommunications. Wavelength division  
24 multiplexing (WDM) techniques are now commonly used to independently transmit a plurality  
25 of signals over a single optical fiber, independent data streams being carried by optical fields  
26 propagating through the optical fiber at a slightly differing optical carrier wavelengths (i.e.,  
27 signal channels). WDM techniques include dense wavelength division multiplexing (DWDM)  
28 schemes, wherein the frequency spacing between adjacent signal channels may range from a few  
29 hundred GHz down to a few GHz. A propagating mode of a particular wavelength must be

1 modulated, independently of other propagating wavelengths, in order to carry a signal. A signal  
2 carried by a particular wavelength channel must be independently accessible for routing from a  
3 particular source to a particular destination. These requirements have previously required  
4 complex and difficult-to-manufacture modulating and switching devices requiring extensive  
5 active alignment procedures during fabrication/assembly, and as a result are quite expensive.  
6 Such devices may require conversion of the optical signals to electronic signals and/or vice  
7 versa, which is quite power consuming and inefficient. In various of the patent applications  
8 cited above a new approach has been disclosed for controlling optical power transmitted through  
9 an optical fiber that relies on the use of resonant circumferential-mode optical resonators, or  
10 other optical resonators, for direct optical coupling to a propagating mode of an optical fiber  
11 resonant with the optical resonator, thereby enabling wavelength-specific modulation, switching,  
12 and routing of optical signals propagating through the optical fiber. A thorough discussion of the  
13 features and advantages of such optical power control devices and techniques, as well as  
14 methods of fabrication, may be found in these applications, already incorporated by reference  
15 herein.

16 [0058] One important element of these latter devices is optical coupling between a fiber-optic  
17 waveguide and a circumferential-mode optical resonator. The circumferential-mode optical  
18 resonator provides wavelength specificity, since only optical signals substantially resonant with  
19 the circumferential-mode optical resonator will be significantly affected by the device. A fiber-  
20 optic waveguide for transmitting the optical signal through the control device is typically  
21 provided with an transverse-coupling segment, where an evanescent portion of the optical signal  
22 extends beyond the waveguide and overlaps a portion of a circumferential optical mode of the  
23 circumferential-mode optical resonator, thereby optically coupling the circumferential-mode  
24 optical resonator and the fiber-optic waveguide. The transverse-coupling segment may take one  
25 of several forms, including an optical fiber taper, D-shaped optical fiber, an optical fiber with a  
26 saddle-shaped concavity in the cladding layer, and/or other functionally equivalent  
27 configurations. These are discussed in detail in various patent applications cited herein.

28 [0059] The circumferential-mode optical resonator structure may comprise a glass micro-  
29 sphere or micro-disk, a fiber-ring resonator, a semiconductor ring/waveguide, or other  
30 functionally equivalent structure, described in detail in various earlier-cited applications. A  
31 high-Q circumferential-mode optical resonator supports relatively narrow-linewidth resonant

1 circumferential optical modes (i.e., having a linewidth consistent with typical linewidths of a  
2 WDM system, TDM system, or other optical data transmission system), which in an optical  
3 power control device may optically couple to optical signals of the fiber-optic waveguide of  
4 substantially resonant optical wavelength. The circumferential-mode optical resonator therefore  
5 provides the wavelength selectivity of the optical power control device. Non-resonant  
6 propagating optical signals pass by the circumferential-mode optical resonator relatively  
7 undisturbed, and are transmitted through the device. By controllably adjusting the loss per round  
8 trip experienced by the circumferential optical mode circulating about the circumferential-mode  
9 optical resonator, the optical power control device may function in either of two modes:

- 10       1)     Switching the circumferential-mode optical resonator between an over-coupled  
11     condition (where the loss per round trip in the circumferential-mode optical resonator is  
12     small compared to the optical coupling between the fiber-optic waveguide and  
13     circumferential-mode optical resonator, and the transmission through the fiber-optic  
14     waveguide past the resonator is large) and the condition of critical coupling (at which  
15     the optical coupling of the fiber-optic waveguide and circumferential-mode optical  
16     resonator is substantially equal to the round trip loss of the circumferential-mode optical  
17     resonator, and substantially all of the optical power is dissipated by/from the  
18     circumferential-mode optical resonator resulting in near zero optical transmission  
19     through the fiber-optic waveguide past the circumferential-mode optical resonator); or  
20       2)     Switching states between the condition of critical coupling (near zero  
21     transmission through the fiber-optic waveguide) and a condition of under-coupling  
22     (where the loss per round trip in the circumferential-mode optical resonator is large  
23     compared to the optical coupling between the fiber-optic waveguide and  
24     circumferential-mode optical resonator, and the transmission through the fiber-optic  
25     waveguide past the circumferential-mode optical resonator is non-zero).

26     **[0060]** For each of these modes of operation, there are essentially two classes of mechanism by  
27     which one can introduce round trip loss to a circulating optical wave (i.e., resonant  
28     circumferential optical mode) in the circumferential-mode resonator. Either optical power of the  
29     circulating wave can be absorbed within the resonator, or it can be gated out of the  
30     circumferential-mode optical resonator into a second optical component, such as a second

1 waveguide or second resonator. The gating may preferably be achieved by control of the optical  
2 coupling between the circumferential-mode optical resonator and the second optical component  
3 and functions rather like a trapdoor. These two general possibilities are both disclosed in several  
4 earlier-cited applications. The current disclosure describes such devices in greater detail,  
5 particularly optical loss components, elements, and/or transducers provided as a separate  
6 component to control optical loss from a circumferential-mode resonator by either of these  
7 means (as distinguished from designs in which the loss control component is an integral part of  
8 the circumferential-mode optical resonator structure).

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1    SUMMARY

2    [0061] Certain aspects of the present invention may overcome one or more aforementioned  
3    drawbacks of the previous art and/or advance the state-of-the-art of resonant optical filters, and  
4    in addition may meet one or more of the following objects:

- 5    [0062] To provide a resonant optical power control device, and methods for fabricating and  
6    using the same, wherein a modulator optical component transverse-coupled to a  
7    circumferential-mode optical resonator provides a controlled level of circumferential-  
8    mode resonator round-trip optical loss, enabling controlled modulation of a level of  
9    transmission of a optical signal power through a transmission fiber-optic waveguide  
10   (transverse-coupled to the circumferential-mode optical resonator) when the optical  
11   signal is substantially resonant with the circumferential optical mode;
- 12   [0063] To provide a resonant optical power control device, and methods for fabricating and  
13   using the same, wherein the modulator optical component comprises an open optical  
14   waveguide (i.e., a modulator optical waveguide);
- 15   [0064] To provide a resonant optical power control device, and methods for fabricating and  
16   using the same, wherein the modulator optical component comprises a closed optical  
17   waveguide (i.e., a modulator optical resonator);
- 18   [0065] To provide a resonant optical power control device, and methods for fabricating and  
19   using the same, wherein the circumferential-mode resonator round-trip optical loss may  
20   be controlled by controlling optical loss of the modulator optical component;
- 21   [0066] To provide a resonant optical power control device, and methods for fabricating and  
22   using the same, wherein the circumferential-mode resonator round-trip optical loss may  
23   be controlled by controlling a modal-index of the modulator optical component;
- 24   [0067] To provide a resonant optical power control device, and methods for fabricating and  
25   using the same, wherein the circumferential-mode resonator round-trip optical loss may  
26   be controlled by controlling optical power transfer from the optical resonator to the  
27   modulator optical component;
- 28   [0068] To provide a resonant optical power control device, and methods for fabricating and  
29   using the same, wherein the circumferential-mode resonator round-trip optical loss may

1       be controlled by controlling a resonant optical frequency of the modulator optical  
2       resonator;

3       **[0069]** To provide a resonant optical power control device, and methods for fabricating and  
4       using the same, wherein the circumferential-mode resonator round-trip optical loss may  
5       be controlled by controlling a resonant optical frequency of the circumferential-mode  
6       optical resonator;

7       **[0070]** To provide a resonant optical power control device, and methods for fabricating and  
8       using the same, wherein the modulator optical component includes an electro-active  
9       material and a modulator control component for applying an electronic control signal  
10      thereto;

11      **[0071]** To provide a resonant optical power control device, and methods for fabricating and  
12      using the same, wherein the modulator optical component includes a non-linear-optical  
13      material and a modulator control component for applying an optical control signal  
14      thereto;

15      **[0072]** To provide a resonant optical power control device, and methods for fabricating and  
16      using the same, wherein the modulator optical component includes a laterally-confined  
17      multi-layer dispersion-engineered waveguide structure;

18      **[0073]** To provide a resonant optical power control device, and methods for fabricating and  
19      using the same, wherein the transmission fiber-optic waveguide, the circumferential-  
20      mode optical resonator, and the modulator optical component, may be accurately,  
21      reliably, and stably positioned and secured within the device; and

22      **[0074]** To provide a resonant optical power control device, and methods for fabricating and  
23      using the same, wherein the transmission fiber-optic waveguide, the circumferential-  
24      mode optical resonator, and the modulator optical component are positioned by and  
25      secured to an alignment device.

26      **[0075]** One or more of the foregoing objects may be achieved in the present invention by an  
27      optical power control device comprising: a) a transmission optical waveguide; b) a resonant  
28      optical component including at least one circumferential-mode optical resonator; c) a modulator  
29      optical component; and d) a modulator control component. The transmission fiber-optic

1 waveguide supports a propagating optical mode (wherein flows the optical signal power to be  
2 controlled by the device) and is provided with an transverse-coupling segment. The  
3 circumferential-mode optical resonator is positioned relative to the transmission fiber-optic  
4 waveguide so as to be transverse-coupled to the transmission optical waveguide. The modulator  
5 optical component is positioned so as to be transverse-coupled to the circumferential-mode  
6 optical resonator. The modulator control component is operatively coupled to the modulator  
7 optical component for modulating, in response to an applied control signal, i) a level of optical  
8 signal power transfer by transverse-coupling between the circumferential-mode optical resonator  
9 and the modulator optical component, ii) a level of optical loss of the modulator optical  
10 component, and iii) a resonant frequency of the modulator optical component, thereby enabling  
11 controlled modulation of a coupling condition between the transmission optical waveguide and  
12 the circumferential optical resonator, in turn enabling controlled modulation of a level of  
13 transmission of the optical signal through the transmission optical waveguide between a higher  
14 operational optical transmission level and a lower operational optical transmission level when  
15 the optical signal is substantially resonant with the resonant optical component.

[0076] The modulator optical component may comprise an open optical waveguide or a closed  
optical waveguide (i.e., a modulator optical resonator). The modulator optical component may  
include an electro-active material and/or a non-linear-optical material, so that application of an  
electronic and/or optical control signal enables control of transmission of the optical signal  
through the transmission optical waveguide by controlling a coupling condition between the  
transmission optical waveguide and the resonant optical component.

[0077] The transmission optical waveguide, the circumferential-mode optical resonator, and  
the modulator optical component may be accurately, reliably, and stably positioned and secured  
within the optical power control device using an alignment device. An alignment device may  
include first and second alignment substrates, the transmission optical waveguide being  
positioned and secured within an alignment groove on the first alignment substrate, the  
modulator optical component being secured to the second alignment substrate, the  
circumferential-mode resonator being positioned and secured on the first or the second substrate,  
the assembled alignment device suitably positioning the modulator optical component,  
circumferential-mode resonator, and transmission optical waveguide relative to each other.

1 [0078] Additional objects and advantages of the present invention may become apparent upon  
2 referring to the preferred and alternative embodiments of the present invention as illustrated in  
3 the drawings and described in the following written description and/or claims.

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1 BRIEF DESCRIPTION OF THE DRAWINGS

2 [0079] Fig. 1 shows a resonant optical filter according to the present invention.

3 [0080] Figs. 2A and 2B show side and partial sectional views, respectively, of a resonant  
4 optical filter according to the present invention.

5 [0081] Figs. 3A and 3B show partial sectional views of a resonant optical filter according to  
6 the present invention.

7 [0082] Figs. 4A and 4B show side and end views, respectively, of a resonant optical filter  
8 according to the present invention.

9 [0083] Figs. 5A, 5B, 5C, 5D, and 5E are schematic diagrams of resonant optical filters  
10 according to the present invention.

11 [0084] Figs. 6A, 6B, and 6C show end, side, and cross-sectional views, respectively, of a  
12 resonant optical filter according to the present invention.

13 [0085] Fig. 7 shows a side view of a resonant optical filter according to the present invention.

14 [0086] Figs. 8A and 8B show side and top views, respectively, of a resonant optical filter  
15 according to the present invention.

16 [0087] Fig. 9 is a flow diagram for fabricating a modulator optical component according to the  
17 present invention.

18 [0088] Fig. 10 is a process diagram for fabricating a modulator optical component according to  
19 the present invention.

20 [0089] Fig. 11 is a process diagram for fabricating a modulator optical component according to  
21 the present invention.

22 [0090] Fig. 12 is a process diagram for fabricating a modulator optical component according to  
23 the present invention.

24 [0091] Fig. 13 is a process diagram for fabricating a modulator optical component according to  
25 the present invention.

26 [0092] Fig. 14 is a process diagram for fabricating a modulator optical component according to  
27 the present invention.

- 1 [0093] Fig. 15 is a flow diagram for fabricating a modulator optical component according to  
2 the present invention.
- 3 [0094] Fig. 16 is a process diagram for fabricating a modulator optical component according to  
4 the present invention.
- 5 [0095] Figs. 17A, 17B, and 17C are two partial sectional views and one top view, respectively,  
6 of a resonant optical filter according to the present invention.
- 7 [0096] Figs. 18A, 18B, and 18C are two partial sectional views and one top view, respectively,  
8 of a resonant optical filter according to the present invention.
- 9 [0097] Figs. 19A and 19B are partial sectional views of a resonant optical filter according to  
10 the present invention.
- 11 [0098] Figs. 20A and 20B are partial sectional views of a resonant optical filter according to  
12 the present invention.
- 13 [0099] Figs. 21A and 21B are partial sectional views of a resonant optical filter according to  
14 the present invention.
- 15 [0100] Figs. 22A and 22B are partial sectional views of a resonant optical filter according to  
16 the present invention.
- 17 [0101] Figs. 23A and 23B are partial sectional views of a resonant optical filter according to  
18 the present invention.
- 19 [0102] Figs. 24A and 24B are partial sectional views of a resonant optical filter according to  
20 the present invention.
- 21 [0103] Fig. 25 illustrates a method for fabricating a circumferential-mode resonator on an  
22 optical fiber according to the present invention. All views are side views, and stippled shading  
23 indicates the presence of an outer coating remaining on the optical fiber.
- 24 [0104] Fig. 26 illustrates a method for fabricating a circumferential-mode resonator on an  
25 optical fiber according to the present invention. All views are side views, and stippled shading  
26 indicates the presence of an outer coating deposited on the optical fiber.
- 27 [0105] Figs 27A and 27B are side sectional views of a circumferential-mode optical resonator  
28 including fiber-taper alignment-an-support structures.

1 [0106] It should be noted that the relative proportions of various structures shown in the  
2 Figures may be distorted to more clearly illustrate the present invention. In particular, the size  
3 differential and resonator thickness of fiber-rings may be greatly exaggerated relative to the  
4 underlying optical fiber diameter in various Figures for clarity. Various metal, semiconductor,  
5 and/or other thin films, layers, and/or coatings may also be shown having disproportionate  
6 and/or exaggerated thicknesses for clarity. Relative dimensions of various waveguides,  
7 resonators, optical fibers/tapers, and so forth may also be distorted, both relative to each other as  
8 well as transverse/longitudinal proportions. The text and incorporated references should be  
9 relied on for the appropriate dimensions of structures shown herein.

10 [0107] It should be noted that most of the Figures may each depict one of several distinct  
11 embodiments of a resonant optical filter according to the present invention. Each set of  
12 embodiments corresponding to a particular Figure are similar in spatial arrangement, but differ in  
13 functional details that are not represented in the Figures. In particular, loss-modulated, index-  
14 modulated, resonance-modulated, interference-modulated embodiments may appear substantially  
15 similar in the Figures. The particular functional aspects of the different embodiments are  
16 described in different text sections that may each refer to one or more common Figures.

1 DETAILED DESCRIPTION OF PREFERRED AND ALTERNATIVE  
2 EMBODIMENTS

3 [0108] For purposes of the present written description and/or claims, “circumferential-mode  
4 optical resonator” (equivalently, CMOR, CM optical resonator, CM resonator, CMR) shall  
5 denote a resonator structure capable of supporting a substantially resonant circumferential  
6 optical mode (equivalently, RCOM), the circumferential optical mode having an evanescent  
7 portion extending beyond the circumferential-mode optical resonator and typically being  
8 substantially confined near the surface of the resonator (near being defined here as within several  
9 microns for visible, near-, or mid-infrared circumferential optical modes). Such a resonator may  
10 also often be referred to as a whispering-gallery-mode optical resonator. Such resonator  
11 structures may include, but are not limited to, spheres, near-spheres, oblate and/or prolate  
12 spheroids, ellipsoids, ovals, ovoids, racetracks, polygons, polyhedra, cylinders, disks, rings,  
13 micro-spheres, micro-disks, micro-rings, fiber-rings, disks and/or rings on substrates, ring or  
14 other closed waveguides, and/or functional equivalents thereof. In particular, the various  
15 circumferential-mode optical resonator structures as disclosed in earlier-cited applications A5  
16 and A15-A18 (denoted collectively as “fiber-rings”, fiber-ring resonator, or FRR’s) are  
17 particularly noted for inclusion as circumferential-mode optical resonators for purposes of this  
18 disclosure. However, other resonator structures may be equivalently employed without  
19 departing from inventive concepts disclose and/or claimed herein. Any resonator having an  
20 evanescent portion of a resonant optical mode or that may otherwise be transverse-coupled to  
21 another optical element (see definition hereinbelow) may be employed as the resonant optical  
22 component of the present invention (i.e., the component that confers wavelength specificity on  
23 the optical power control device). Optical resonator structures disclosed in earlier-cited  
24 applications A12 and A20 (denoted collectively as “MLR rings”) are particularly noted for  
25 inclusion as optical resonators suitable for use in the present invention. Although the term  
26 “circumferential-mode optical resonator” is used throughout the remainder of the present  
27 disclosure, it should be understood that any optical resonator that may be transverse-coupled to a  
28 transmission waveguide and/or to an optical modulator as disclosed herein shall be considered  
29 functionally equivalent to a circumferential-mode optical resonator. It should also be noted that  
30 the terms “resonant optical component”, “optical resonator”, “circumferential-mode optical  
31 resonator”, and so forth may encompass both single optical resonators as well as coupled

1 systems of multiple optical resonators, unless a single- or multiple-resonator device is  
2 specifically designated in the text.

3 [0109] For purposes of the present written description and/or claims, a “transmission fiber-  
4 optic waveguide” (equivalently, transmission fiber-optic, transmission optical fiber, TFOWG) is  
5 particularly noted for inclusion as a transmission optical waveguide, and shall denote an optical  
6 fiber (polarization-maintaining or otherwise) provided with a transverse-coupling segment where  
7 an evanescent portion of an optical signal may extend beyond the fiber-optic waveguide and  
8 overlap a portion of some other optical mode, thereby enabling transverse-coupling between the  
9 transmission optical waveguide and another optical component. Such a transmission fiber-optic  
10 waveguide may comprise an fiber-optic taper, a D-shaped optical fiber, an optical fiber with a  
11 saddle-shaped concavity in the cladding layer, an optical fiber with a side-polished flattened  
12 portion, and/or functional equivalents. Such transmission optical waveguides are described in  
13 further detail in earlier-cited applications A1-A6 and A15-A18. Such transmission fiber-optic  
14 waveguides typically serve to facilitate insertion of resonant optical filters according to the  
15 present invention into an optical signal transmission system.

16 [0110] For purposes of the written description and/or claims, “transverse-coupling” (also  
17 referred to as transverse optical coupling, evanescent coupling, evanescent optical coupling,  
18 directional coupling, directional optical coupling) shall generally denote those situations in  
19 which two optical components, each capable of supporting a propagating and/or resonant optical  
20 mode and at least one having an evanescent portion of its optical mode extending beyond the  
21 respective optical component, are optically coupled by at least partial transverse spatial overlap  
22 of the evanescent portion of one optical mode with at least a portion of the other optical mode.  
23 The amount, strength, level, or degree of optical power transfer from one optical component to  
24 the other through such transverse optical coupling depends on the spatial extent of the overlap  
25 (both transverse and longitudinal), the spectral properties of the respective optical modes, and  
26 the relative spatial phase matching of the respective optical modes (also referred to as modal  
27 index matching). To transfer optical power most efficiently, the respective modal indices of the  
28 optical modes (equivalently, the respective modal propagation constants), each in its respective  
29 optical component, must be substantially equal. Mismatch between these modal indices  
30 decreases the amount of optical power transferred by transverse coupling between the optical  
31 components, since the coupled modes get further out of phase with each other as each propagates

1 within its respective optical component and the direction of the optical power transfer eventually  
 2 reverses itself. The propagation distance over which the modes interact (i.e., the effective  
 3 interaction length) and the degree of modal-index matching (or mis-matching) together influence  
 4 the overall flow of optical power between the coupled modes. Optical power transfer between  
 5 the coupled modes oscillates with a characteristic amplitude and spatial period as the modes  
 6 propagate, each in its respective optical component.

7 [0111] Neglecting the effects of optical loss in the optical components, an ideal system  
 8 consisting of two coupled modes can be characterized by the following coupled system of  
 9 equations:

$$\begin{aligned}\frac{\partial E_1}{\partial z} &= i\beta_1 E_1 + i\kappa E_2 \\ \frac{\partial E_2}{\partial z} &= i\beta_2 E_2 + i\kappa^* E_1\end{aligned}$$

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 11 where the following definitions apply:  
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*E<sub>1,2</sub>* amplitudes of the coupled fields;

*β<sub>1,2</sub>* propagation constants of the coupled fields;

*κ* coupling amplitude resulting from spatial overlap of the fields;

*z* propagation distance coordinate.

For the purpose of illustration, it is assumed that the coupling amplitude *κ* is constant over an interaction distance *L*. Then, an incident field of amplitude *E<sub>1</sub>* that is spatially confined to the first optical component before interaction will couple to the other wave guide with a resultant field amplitude *E<sub>2</sub>(L)* at *z=L* (where we define *z=0* as the start of the coupling region) given by the following expression,

$$\frac{|E_2(L)|^2}{|E_1(0)|^2} = \frac{|\kappa|^2}{q^2} \sin^2(qL)$$

$$q^2 = |\kappa|^2 + \frac{1}{4} \Delta\beta^2$$

Consider the modal-index mismatch term ( $\Delta\beta=\beta_2-\beta_1$ ) and the interaction length in this expression. As is well known, a condition of modal-index mismatch between the two spatial

1 modes causes an oscillatory power transfer to occur between the waveguides as the interaction  
2 length is varied. The spatial period of this oscillation, a so-called “beat length”, can be defined as  
3 the distance over which power cycles back and forth between the guides. Greater amounts of  
4 modal-index mismatch will reduce the beat length. Also note that the absolute magnitude of  
5 power transfer will diminish with increasing modal-index mismatch. Finally, it is apparent that  
6 increased amounts of interaction length and/or increased modal-index mismatch will introduce  
7 an increased spectral selectivity to the optical power transfer.

8 [0112] By controlling the modal-index mismatch and/or transverse spatial overlap between  
9 optical modes, these characteristics may be exploited for controlling optical power transfer  
10 between optical components. For example, by altering the modal-index mismatch, a device may  
11 be switched from a first condition, in which a certain fraction of optical power is transferred  
12 from a first optical mode in a first optical component to a second optical mode in a second  
13 optical component (modal-index mismatch set so that the effective interaction length is about  
14 half of the characteristic spatial period described above), to a second condition in which little or  
15 no optical power is transferred (modal-index mismatch set so that the effective interaction length  
16 is about equal to the characteristic spatial period). Further discussion of optical coupling may be  
17 found in Fundamentals of Photonics by B. E. A. Saleh and M. C. Teich (Wiley, New York,  
18 1991), hereby incorporated by reference in its entirety as if fully set forth herein. Particular  
19 attention is called to Chapters 7 and 18.

20 [0113] For purposes of the written description and/or claims, “index” may denote the bulk  
21 refractive index of a particular material (also referred to herein as a “material index”) or may  
22 denote the propagation constant of a particular optical mode in a particular optical component  
23 (referred to herein as a “modal index”). As referred to herein, the term “low-index” shall denote  
24 any materials and/or optical structures having an index less than about 2.5, while “high-index”  
25 shall denote any materials and/or structures having an index greater than about 2.5. Within these  
26 bounds, “low-index” may preferably refer to silicas, glasses, oxides, polymers, and any other  
27 optical materials having indices typically between about 1.3 and about 1.8, and may include  
28 optical fiber, optical waveguides, and any other optical components incorporating such materials.  
29 Similarly, “high-index” may preferably refer to materials such as semiconductors or any other  
30 material having indices of about 3 or greater. The terms “high-index” and “low-index” are to be  
31 distinguished from the terms “lower-index” and “higher-index”, also employed herein. “Low-

1 index” and “high-index” refer to an absolute numerical value of the index (greater than or less  
2 than about 2.5), while “lower-index” and “higher-index” are relative terms indicating which of  
3 two materials has the larger index, regardless of the absolute numerical values of the indices.

4 [0114] For purposes of the written description and/or claims, the term “multi-layer reflector  
5 stack” or “MLR stack” or “MLR” shall denote a multi-layer structure wherein the layer index  
6 varies with each successive layer of the stack, yielding an optical structure having wavelength-  
7 dependent optical properties. An common example of such a structure is a distributed Bragg  
8 reflector (DBR), which may typically comprise alternating quarter-wave-thickness layers of a  
9 higher-index material and a lower-index material. The term “multi-layer reflector stack” shall  
10 denote any periodic, partially periodic, multi-periodic, quasi-periodic, graded-index, and/or  
11 similar multi-layer varying-index structure.

12 [0115] For purposes of the written description and/or claims, the term “electro-active” shall  
13 denote any material that may exhibit electro-optic and/or electro-absorptive properties. The term  
14 “non-linear-optical” shall denote any material that may exhibit non-linear optical properties,  
15 including both resonant and non-resonant non-linear-optical properties.

16 [0116] It should be noted that optical waveguides and resonators as described herein, optical  
17 modulators, interferometers, couplers, routers, add-drop filters, switches, and other devices  
18 incorporating such waveguides and/or resonators, their fabrication, and their use according to the  
19 present invention are intended primarily for handling optical modes having wavelengths between  
20 about 0.8  $\mu\text{m}$  and about 1.0  $\mu\text{m}$  (the wavelength range typically utilized for so-called short-haul  
21 fiber-optic telecommunications) and optical modes having wavelengths between about 1.2  $\mu\text{m}$   
22 and about 1.7  $\mu\text{m}$  (the wavelength range typically utilized for so-called long-haul fiber-optic  
23 telecommunications). However, these devices, methods of fabrication, and methods of use may  
24 be adapted for use at any desired wavelength while remaining within the scope of inventive  
25 concepts disclosed and/or claimed herein.

26 [0117] A typical resonant optical modulator according to the present invention is shown  
27 schematically in Fig. 1. In subsequent Figures, specific embodiments for transmission optical  
28 waveguide 110, circumferential-mode resonator 120, and/or alignment structures therefor may  
29 be shown. These are illustrative and exemplary, and should not be construed as limiting the  
30 scope of the present invention as shown, described, and/or claimed except when specifically

1 recited in a particular claim. Transmission waveguide 110 is typically an optical fiber taper,  
2 although a side etched optical fiber (as in earlier-cited application A6) is also shown, and any  
3 other transmission waveguide having a suitable transverse-coupling segment may be  
4 equivalently employed. Circumferential-mode resonator 120 is typically shown as fiber-ring  
5 resonator (as in earlier-cited applications A5 and A15-A18), although any other optical resonator  
6 suitable for transverse-coupling to a transmission waveguide and a modulator optical component  
7 may be equivalently employed. An optical signal enters an input end 112 of transmission fiber-  
8 optic waveguide 110, and exits an output end 114 of transmission waveguide 110. Transmission  
9 waveguide 110 is provided with a transverse-coupling segment 116, that may include a fiber-  
10 optic-taper segment of a fiber-optic waveguide (as described, for example, in earlier-cited  
11 applications A1 through A5), a saddle- or pit-shaped transverse-coupling portion of a cladding  
12 layer surface of a fiber-optic waveguide (as described in earlier-cited application A6), or other  
13 functionally equivalent structure. A circumferential-mode optical resonator 120 supports a  
14 substantially resonant circumferential optical mode. The circumferential-mode optical resonator  
15 120 is positioned relative to the transverse-coupling segment of the transmission waveguide 110  
16 so as to be transverse-coupled thereto. The circumferential-mode optical resonator 120 provides  
17 the wavelength selectivity of modulator. Unless the optical signal is substantially resonant with  
18 the circumferential-mode resonator 120, optical signal power transfer into and/or dissipation of  
19 optical signal power from the circumferential-mode resonator 120 is/are negligible, and the  
20 optical signal is transmitted through the transmission waveguide 110 substantially unaffected by  
21 the presence of resonator 120 or the operational state of control device.

22 [0118] In contrast, when the optical signal is substantially resonant with the circumferential-  
23 mode resonator 120, optical signal power transfer into and circulation within resonator 120 may  
24 be quite substantial. For a relatively high-Q circumferential-mode optical resonator (on the order  
25 of  $10^6$  may be achieved;  $10^4$ - $10^5$  typically employed in devices according to the present  
26 invention), the level of circulating optical signal power in the circumferential optical mode may  
27 reach a level many times higher than the incident optical signal power. Slight changes in the  
28 optical loss per round trip for this circulating radiation dramatically affects the level of  
29 transmission of the optical signal through the transmission waveguide 110. By controllably  
30 adjusting this optical loss per round trip, the resonant optical modulator may function in either of  
31 two modes:

1        1)     Switching the circumferential-mode optical resonator between an over-coupled  
2        condition (where the loss per round trip in the circumferential-mode optical resonator is  
3        small compared to the optical coupling between the fiber-optic waveguide and  
4        circumferential-mode optical resonator, and the transmission through the fiber-optic  
5        waveguide past the resonator is large) and the condition of critical coupling (at which  
6        the optical coupling of the fiber-optic waveguide and circumferential-mode optical  
7        resonator is substantially equal to the round trip loss of the circumferential-mode optical  
8        resonator, and substantially all of the optical power is dissipated by/from the  
9        circumferential-mode optical resonator resulting in near zero optical transmission  
10      through the fiber-optic waveguide past the circumferential-mode optical resonator); or

11        2)     Switching states between the condition of critical coupling (near zero  
12      transmission through the fiber-optic waveguide) and a condition of under-coupling  
13      (where the loss per round trip in the circumferential-mode optical resonator is large  
14      compared to the optical coupling between the fiber-optic waveguide and  
15      circumferential-mode optical resonator, and the transmission through the fiber-optic  
16      waveguide past the circumferential-mode optical resonator is non-zero).

17      [0119] For purposes of the present written description and/or claims, it shall be assumed  
18      (unless specifically stated otherwise) that the optical signal to be modulated is substantially  
19      resonant with the resonant optical component that includes at least one circumferential-mode  
20      optical resonator.

21      [0120] A preferred circumferential-mode optical resonator is a ring resonator fabricated on an  
22      optical fiber as disclosed in earlier-cited applications A5 and A15-A18, referred to a fiber-ring  
23      resonator (FRR). As shown in Fig. 25, a fiber-ring resonator may typically include a transverse  
24      resonator fiber segment 2610 having a circumferential optical pathlength sufficiently longer than  
25      longitudinally adjacent portions 2620 of surrounding fiber segments 2630 so as to support one or  
26      more resonant circumferential optical modes confined near the resonator fiber segment. The  
27      optical pathlength differential may be most readily provided by providing a radius differential  
28      between the resonator fiber segment 2610 and the longitudinally adjacent portions 2620 of the  
29      surrounding fiber segments 2630 (the resonator fiber segment having the larger radius). For use  
30      in a resonant optical modulator according to the present invention, a fiber-ring resonator may

1 have a diameter ranging between about 10  $\mu\text{m}$  and a few millimeters, preferably between about  
2 20  $\mu\text{m}$  and about 200  $\mu\text{m}$ , and most preferably between about 100  $\mu\text{m}$  and about 150  $\mu\text{m}$ . The  
3 fiber-ring resonator may have a radius differential (resonator segment radius greater than the  
4 adjacent portions of the surrounding segments of the resonator fiber) ranging between about 0.1  
5  $\mu\text{m}$  and about 20  $\mu\text{m}$ , preferably between about 0.5  $\mu\text{m}$  and about 1.5  $\mu\text{m}$ . The width of the  
6 resonator segment may range between about 1  $\mu\text{m}$  and about 10  $\mu\text{m}$ , preferably between about 2  
7  $\mu\text{m}$  and about 4  $\mu\text{m}$ . These size differentials and resonator widths are generally sufficient to  
8 substantially confine a circumferential mode with minimum number of nodes along the fiber axis  
9 or in the radial direction and confined at least partially within the resonator segment, while not  
10 confining higher-order modes as well (if at all).

11 [0121] It has been observed, however, that a circumferential-mode resonator having a diameter  
12 of about 125  $\mu\text{m}$ , a size differential of 1-2  $\mu\text{m}$ , and a resonator segment thickness of about 5  $\mu\text{m}$   
13 may support a circumferential mode with minimum number of nodes along the fiber axis or in  
14 the radial direction, but also higher-spatial-order circumferential-mode modes having planar  
15 nodal surfaces perpendicular to the axis of the resonator segment. These higher-spatial-order  
16 modes are frequency shifted with respect to the lowest-order mode, thereby degrading the  
17 frequency selectivity (i.e., decreased frequency spacing between modes) of the circumferential-  
18 mode resonator. This problem may be mitigated in several ways. In a first method, it has been  
19 observed that a smaller size differential between the resonator segment and the adjacent portions  
20 (between about 0.5  $\mu\text{m}$  and about 1.5  $\mu\text{m}$ ) confines the circumferential optical modes more  
21 weakly than a larger size differential. This effect becomes substantially more pronounced for  
22 higher-spatial-order modes, which extend further beyond the resonator segment than lower-order  
23 modes. Sufficient reduction of the size differential results in substantial suppression of all  
24 higher-order modes. In a second method, the thickness of the resonator segment may be reduced  
25 from about 5  $\mu\text{m}$  to about 1  $\mu\text{m}$  in order to remove higher order spatial modes.

26 [0122] Alternatively, the fiber-ring resonator may be provided with mode suppressor structures  
27 for suppressing de-localized (i.e., higher-order) optical modes supported by the fiber-ring  
28 resonator and/or resonator fiber. Such mode suppressors may be adapted for selectively  
29 providing optical loss for undesirable, de-localized optical modes, while leaving the desired  
30 circumferential optical mode substantially undisturbed. Such mode suppressors may take the  
31 form of a fiber coating left in place on the fiber after fabrication of the fiber-ring resonator (Fig.

1 25), or a coating deposited on the resonator fiber as a separate fabrication step (Fig. 26). Such a  
2 coating may absorb or scatter light at the relevant wavelength, and may be provided on  
3 surrounding segments of the resonator fiber. A preferred coating is a hermetic carbon coating  
4 used as an etch mask for fabricating the fiber-ring resonator. In the mask removal step, the  
5 hermetic carbon coating may be removed from only the resonator fiber segment 2610, but left on  
6 surrounding fiber segments 2630 to provide de-localized mode suppression (Fig. 25).  
7 Alternatively, scattering and/or absorbing material may be deposited to form a de-localized  
8 mode suppressor (Fig. 26). Such mode-suppressor structures may extend around the entire  
9 circumference of the resonator fiber, or around only a portion thereof.

10 [0123] An alternative method for dealing with de-localized optical modes is the use of optical  
11 fiber having an absorbing and/or scattering core. Such a core serves to suppress delocalized  
12 optical modes while leaving desired circumferential optical modes substantially undisturbed.  
13 Such a fiber may be manufactured with an absorbing and/or scattering core, or hollow-core  
14 optical fiber may be employed, and the hollow core filled with absorbing and/or scattering  
15 material of any suitable type.

16 [0124] Figs. 27A and 27B show additional alignment members provided on or near a fiber-ring  
17 resonator segment 2610. In a resonant optical filter according to the present invention, a  
18 transmission fiber-optic waveguide is typically provided with a fiber-optic-taper segment 2616  
19 to serve as a transverse-coupling segment. To reproducibly establish and stably maintain  
20 transverse-coupling between the fiber-optic-taper segment and the fiber-ring resonator, a taper-  
21 positioner may be provided on the resonator fiber. In Fig. 27A, a radially-extending radially-  
22 tapered transverse flange 2611 is provided on the resonator fiber adjacent to the fiber segment  
23 2610. This taper positioner may be fabricated using any of the cylindrical processing methods  
24 disclosed in earlier-cited application A5-A6 and A15-A18. A preferred method may include a  
25 modification of the process illustrated in Fig. 25 for surface-masked etching of the resonator  
26 fiber. In addition to the two unmasked rings shown in Fig. 25, a very narrow line is machined  
27 through the resonator segment mask ring at a distance from the edge about equal to twice the  
28 desired etch depth (i.e., radius differential between the resonator segment and the etched adjacent  
29 portions), thereby dividing the masked resonator segment ring into a main masked ring and a  
30 secondary masked ring. The etch process is permitted to proceed (both longitudinally as well as  
31 radially) until two of the etched portions just meet (i.e., when the secondary masked ring just

1 disappears), yielding the radially-extending radially-tapered transverse flange 2611 shown in  
2 Fig. 27A. The taper-positioner serves to provide reproducible and stable positioning of the fiber-  
3 optic-taper segment 2616 against the flange 2611 and the resonator segment 2610. A portion of  
4 the secondary masked ring may be machined away prior to etching, so that the flange 2611  
5 extends only partly around the circumference of the resonator fiber, thereby suppressing the  
6 ability of flange 2611 to support undesirable optical modes.

7 [0125] An alternative taper positioner is illustrated in Fig. 27B, comprising a pair of  
8 longitudinally-juxtaposed radially-extending radially-tapered transverse flanges 2612 positioned  
9 on outer circumference of the resonator segment 2610 so that the fiber-optic-taper segment may  
10 rest on paired flanges. Any of the cylindrical processing methods disclosed in earlier-cited  
11 applications A5-A6 and A15-A18 may be employed to produce the paired flanges 2612. A  
12 preferred method may comprise a two-step implementation of the surface-masked etching  
13 process of Fig. 25. After surface-masked etching to produce the fiber-ring resonator segment  
14 2610, a narrow line is machined in the mask material around the longitudinal midline of the  
15 masked fiber ring. Upon etching, the concave groove is formed between two circumferential  
16 ridges. The etch process is permitted to continue until the flat tops of the ridges just disappear.  
17 A fiber-optic-taper segment 2616 may then rest securely against the paired flanges 2612 for  
18 reproducibly established and stably maintained evanescent optical coupling between the fiber-  
19 optic-taper segment 2616 and resonator segment 2610.

20 [0126] In addition to stable mechanical engagement of the fiber-optic-taper segment and the  
21 resonator segment, flanges 2611 and 2612 provide other beneficial effects. It has been observed  
22 that when a fiber-optic-taper segment is brought into direct mechanical contact with the outer  
23 circumference of a fiber-ring resonator, the proximity of the fiber-optic-taper segment seems to  
24 induce coupling between undesirable, delocalized optical modes of the fiber-ring resonator  
25 and/or resonator fiber and/or higher order modes of the fiber optic taper. This manifests itself as  
26 an unacceptably large optical loss of the fiber-ring resonator (over and above the desired  
27 resonator optical losses due to transverse-coupling to the fiber-optic taper, modulator optical  
28 component, and/or other component of the resonant optical modulator). By displacing the fiber-  
29 optic-taper segment from the midline of the fiber ring resonator outer circumference (either  
30 longitudinally or radially), the undesirable coupling to these delocalized optical modes can be  
31 substantially reduced or eliminated, albeit the expense of reduced coupling strength between the

1 fiber-optic-taper segment and the fiber-ring resonator. Flange 2611 serves to position the fiber-  
2 optic taper segment 2616 in a longitudinally-displaced position relative to fiber-ring resonator  
3 segment 2610, while flanges 2612 serve to position fiber-optic-taper segment 2616 in a radially-  
4 displaced position relative to fiber-ring resonator segment 2610.

5 [0127] The mechanical stability of fiber-optic-taper segment 2616 transverse-coupled to fiber-  
6 ring resonator segment 2610 with taper positioner 2611 or 2612 may be further enhanced by  
7 tacking or welding the taper segment to the fiber ring resonator and/or taper positioner. A  
8 preferred method for doing so comprises “spot welding” the taper to the positioner or fiber-ring  
9 with a short burst from a CO<sub>2</sub> laser. The mechanical stability of the optical system is enhanced  
10 while typically introducing only minimal additional insertion loss into the fiber-optic-tapered  
11 waveguide.

12 [0128] Referring again to Fig. 1, a modulator optical component 130 is positioned relative to  
13 circumferential-mode optical resonator 120 so as to transverse-coupled thereto. Modulator  
14 optical component 130 serves to enable controlled adjustment of the round trip optical loss of  
15 resonator 120 between over-, critical-, and/or under-coupled conditions in one of several of  
16 ways: i) modulator optical component 130 may provide a controlled level of direct optical loss  
17 of the circumferential optical mode (collectively referred to herein as “loss-modulated” or more  
18 specifically “absorption-modulated” devices); ii) a level of transverse-coupling between  
19 circumferential-mode optical resonator 120 and modulator optical component 130 may be  
20 controlled, with optical signal power transferred from resonator 120 into modulator optical  
21 component 130 absorbed within, transmitted away from, and/or otherwise dissipated from the  
22 modulator optical component 130 (collectively referred to herein as “coupling-modulated” or  
23 more specifically “index-modulated” devices); iii) a resonant frequency of a resonant modulator  
24 optical component 130 may be controlled, so that modulator optical component only provides  
25 loss for the circumferential optical mode when a modulator resonance frequency substantially  
26 coincides with the circumferential-mode frequency (collectively referred to herein as  
27 “resonance-modulated” devices); and iv) a modulator optical component 130 may be transverse-  
28 coupled to resonator 120 at two separate points and the modulator modal index may be  
29 controlled, enabling interferometric control of the round-trip loss of resonator 120 (collectively  
30 referred to herein as “interference-modulated” devices). Modulator control component(s) 170  
31 is/are operatively coupled to the modulator optical component 130 for enabling control of the

1 round trip loss of the circumferential-mode resonator 120 by application of a control signal, in  
2 turn enabling controlled modulation of transmission of the optical signal through the  
3 transmission waveguide 110.

4 [0129] In a first group of embodiments of the present invention, a level of direct optical loss of  
5 the circumferential optical mode induced by the modulator optical component is controlled to  
6 enable controlled modulation of transmission of the optical signal through the transmission  
7 waveguide. The modulator optical component in these so-called “loss-modulated” or  
8 “absorption-modulated” embodiments may comprise an open optical waveguide structure (in  
9 which an optical mode of the waveguide does not follow a closed path and re-circulate and/or  
10 resonate within the waveguide; referred to hereinafter as a “modulator waveguide”), or may  
11 comprise an ring, resonator (including a second circumferential-mode optical resonator), or other  
12 closed optical waveguide structure (in which an optical mode of the waveguide may re-circulate  
13 and/or resonate; referred to collectively hereinafter as a “modulator resonator”). In either case,  
14 the modulator optical component is positioned so that an evanescent portion of the  
15 circumferential optical mode at least partially spatially overlaps an optical mode of the  
16 modulator optical component. A modulator optical component incorporating material whose  
17 optical loss, at the wavelength of the circumferential optical mode, can be controlled thereby  
18 enables control of the round trip optical loss experienced by the circumferential optical mode in  
19 the circumferential-mode resonator, in turn achieving the desired goal of controlled modulation  
20 of transmission of the optical signal through the transmission waveguide as described above.

21 [0130] Absorption-modulated embodiments of an optical power control device according to the  
22 present invention are shown in Figs. 2A, 2B, 3A, and 3B in which the modulator optical  
23 component comprises an open modulator optical waveguide positioned tangentially with respect  
24 to the circumferential-mode optical resonator. Transmission waveguide 110 is shown as a fiber-  
25 optic taper. A fiber-optic waveguide having a transverse-coupling portion of the cladding layer  
26 surface as described in detail in earlier-cited application A6, or other fiber-optic waveguide  
27 having a transverse-coupling portion could be equivalently employed. Circumferential-mode  
28 optical resonator 120 is shown in Figs. 2A, 2B, 3A, and 3B as a fiber-ring resonator as described  
29 in detail in earlier-cited applications A5 and A15-A18. Other circumferential-mode resonator  
30 structures could be equivalently employed, including but not limited to a rings, spheres or near-  
31 spheres, disks, microspheres, microdisks, or other resonator geometry as recited hereinabove. In

1 Figs. 2A and 2B, the modulator optical component is a slab waveguide 132 in substantial  
2 tangential engagement with circumferential-mode resonator 120, either in direct mechanical  
3 contact, or positioned at a specific distance from the circumferential-mode resonator to yield a  
4 desired level of transverse-coupling.

5 [0131] An evanescent portion of the circumferential optical mode supported by  
6 circumferential-mode resonator 120 may extend radially beyond the circumference thereof, and  
7 may therefore spatially overlap a portion of an optical mode of the slab waveguide 132.  
8 Absorption-modulated slab waveguide 132 may preferably be fabricated incorporating a material  
9 having an optical loss (typically optical absorption), at the wavelength of the circumferential  
10 optical mode, which may be controlled by a modulator control component. The optical  
11 absorption per unit length in the interaction region is preferably sufficiently large to enable the  
12 circumferential-mode resonator round trip optical loss to reach a level comparable to the optical  
13 coupling between the transmission waveguide 110 and the resonator 120 (i.e., to achieve critical  
14 coupling; typically loss on the order of about 0.5% to about 5% per round trip is needed to yield  
15 linewidths consistent with typical WDM, TDM, or other optical data transmission systems;  
16 typically on the order of 1-40 GHz), or alternatively to enable the circumferential-mode  
17 resonator round trip loss to exceed critical coupling. This may be difficult to achieve, since the  
18 interaction region (i.e., the volume of overlap between the evanescent portion of the  
19 circumferential optical mode and the slab waveguide) is typically limited in spatial extent by the  
20 size and curvature of the circumferential-mode resonator. The slab waveguide should be kept  
21 thin (comparable to the radial extent of the evanescent portion of the circumferential optical  
22 mode beyond the circumference of resonator 120) and the index of refraction of any substantially  
23 homogeneous medium in contact with the face of the slab opposite the circumferential-mode  
24 resonator (i.e., a substrate or cladding layer) must be less than the refractive index of the slab  
25 waveguide and no greater than the refractive index of the circumferential-mode resonator. In  
26 this way, optical power not absorbed by slab waveguide 132 is confined within waveguide 132  
27 near resonator 110, thereby substantially eliminating undesired optical loss. Otherwise optical  
28 power coupled from the circumferential-mode resonator 120 into slab waveguide 132 could  
29 propagate away from resonator 110 and be lost.

30 [0132] Modal index mismatch (i.e., phase mismatch) between the circumferential optical mode  
31 and the slab waveguide must be carefully controlled so that, by switching the slab waveguide

1 absorption between two operational levels, the round trip optical loss of the circumferential-  
2 mode optical resonator may be switched between under- and critically-coupled conditions at the  
3 fiber-optic waveguide/resonator junction, or between critically- and over-coupled conditions at  
4 the fiber-optic waveguide/resonator junction. For example, the slab waveguide material might  
5 be chosen to yield a relatively large phase mismatch, thereby limiting the transfer of optical  
6 power to the slab (characteristic spatial period short compared to interaction length) and  
7 resulting in an over-coupled condition at the fiber-optic waveguide/resonator junction, while the  
8 optical absorption of the slab may be switched to a sufficiently high level to result in critical-  
9 coupling at the fiber-optic waveguide/resonator junction in spite of the phase mismatch (the  
10 significance of phase mismatch tends to decrease with increasing absorption in the modulator  
11 waveguide, since there is less optical power available to “back-couple” into the resonator). In a  
12 second example, the slab and circumferential-mode resonator might be well phase-matched and  
13 the optical loss of the slab chosen to produce a critical-coupling condition at the fiber-optic  
14 waveguide/resonator junction, while the optical absorption of the slab may be switched to a  
15 higher level to yield an under-coupled condition at the fiber-optic waveguide/resonator junction.  
16 Many other schemes and combinations of modal-index match/mismatch and operative levels of  
17 optical absorption of the slab waveguide may be employed while remaining within the scope of  
18 inventive concepts disclosed and/or claimed herein. For a given circumferential-mode optical  
19 resonator geometry, slab waveguide material, and so forth, some experimentation is typically  
20 required to determine the level of transverse-coupling, and the appropriate levels of slab  
21 waveguide optical loss to produce the desired modulation of the circumferential-mode resonator  
22 round trip loss.

23 [0133] In Figs. 3A and 3B, the modulator optical component is a loss- or absorption-modulated  
24 laterally-confined waveguide 134 (referred to as a “2D waveguide” in earlier-cited applications)  
25 on a substrate 136 and positioned tangentially with respect to circumferential-mode optical  
26 resonator 120. Many of the same considerations applicable to the absorption-modulated slab  
27 waveguide embodiment of Figs. 2A and 2B apply to the absorption-controlled laterally-confined  
28 waveguide embodiment of Figs. 3A and 3B. The laterally-confined waveguide 134 may  
29 preferably be fabricated incorporating a material having an optical absorption at the wavelength  
30 of the circumferential optical mode that may be controlled by a modulator control component,  
31 and which may produce circumferential-mode resonator round trip loss sufficient to achieve

critical coupling. Modal index mismatch between the laterally-confined waveguide and the circumferential-mode optical resonator must be controlled in the manner described hereinabove for the absorption-controlled slab waveguide. In addition to the laterally-confined waveguide material and the substrate material, the transverse geometry of the laterally-confined waveguide must also be chosen to yield the desired spatial overlap and modal-index match/mismatch properties.

[0134] The optical absorption of absorption-modulated slab waveguide 132 or laterally-confined waveguide 134 may be controlled by electronic, optical, and/or other means. For example, a quantum well, multi-quantum well (MQW), other semi-conductor, or other functionally equivalent material may be incorporated into the modulator waveguide as an electro-absorptive material, wherein the optical absorption of the modulator waveguide may be altered by application of a control electric field. A modulator control component may comprise control electrodes suitably positioned to apply the control electric field. Alternatively, the optical absorption by such materials may be controlled by injection of current into the material. The presence of additional charge carriers (electrons and/or holes, as the case may be) may serve to increase or decrease the optical absorption of the waveguide material, depending on the bandgap, band structure, and/or doping of the electro-absorptive material and the wavelength of the optical mode to be modulated. Control electrodes or other electrical contacts may serve to inject a control electrical current. Optical excitation of such materials may also serve to generate charge carriers, thereby enabling control of the waveguide optical absorption by application of an optical control signal. Other classes of materials exhibiting photo-bleaching, excited state absorption, saturable absorption, non-linear optical absorption, and/or resonant non-linear-optical properties may be equivalently incorporated into the modulator waveguide to enable control of the waveguide optical absorption by application of an optical control signal.

[0135] A preferred material for fabricating slab waveguide 132 and/or laterally-confined waveguide 134 comprises a multi-quantum well (MQW) material comprising alternating layers of i) quantum well layers of a material having a bulk bandgap close to or only slightly larger (within about 10 meV to 30 meV, for example) than the photon energy of the circumferential optical mode, and ii) barrier layers having a bandgap substantially larger than the photon energy of the optical signal. The bandgaps referred to here are not the bulk bandgaps for the various materials, but the bandgaps of the materials as incorporated as individual layers of a multi-layer

1 structures described. The MQW material may be surrounded by a pair of contact layers (doped  
2 or otherwise) for facilitating electrical contact to the control electrodes. Delta-doping of the  
3 contact layers may be preferred, to minimize unwanted diffusion of dopant(s) into the MQW  
4 material. The control signal may comprise a control voltage applied across the electrodes,  
5 thereby applying a control electric field substantially normal to the layers of the MQW material.  
6 This electric field may red-shift resonance(s) of the MQW material with respect to the frequency  
7 of the circumferential optical mode through a quantum-confined Stark effect (QCSE), a Franz-  
8 Keldysh effect (FKE), a quantum-confined Franz-Keldysh effect (QCFKE), or other similar  
9 mechanism. Typically, the electro-absorptive MQW material would be chosen having a  
10 resonance i) slightly above the photon energy of the circumferential optical mode in the absence  
11 of a control electric field, and ii) slightly below the photon energy of the circumferential optical  
12 mode when red-shifted by application of the control electric field. In this way application of the  
13 control signal alters the optical loss experienced by the circumferential optical mode, in turn  
14 altering the transmission level of the optical signal through the transmission waveguide.

[0136] In an exemplary embodiment for controlling wavelengths typically used for long-haul  
1 fiber-optic telecommunications (between about 1.2  $\mu\text{m}$  and about 1.7  $\mu\text{m}$ ), the quantum well  
2 layers, barrier layers, and doped contact layers may comprise InGaAsP, the quantum well layers  
3 may be between about 7 nm thick and about 15 nm thick with a bulk bandgap between about 1.3  
4  $\mu\text{m}$  and about 1.6  $\mu\text{m}$ , the barrier layers may be between about 20  $\mu\text{m}$  thick and about 50 nm  
5 thick with a bulk bandgap between about 1.0  $\mu\text{m}$  and about 1.4  $\mu\text{m}$ , and the doped contact layers  
6 may be between about 20 nm thick and about 100 nm thick. In a preferred embodiment, the  
7 quantum well layers may be about 10 nm thick with a bulk bandgap of about 1.6  $\mu\text{m}$ , the barrier  
8 layers may be about 20 nm thick with a bandgap of about 1.2  $\mu\text{m}$ , and the delta-doped contact  
9 layers may be about 50 nm thick. Many such MQW materials are readily available  
10 commercially, and may be specified by layer thickness, layer bandgap, and layer composition.  
11 The bulk bandgap of a particular layer material may be generally well-known and determined by  
12 the precise composition/stoichiometry of the material, while the layer bandgap may often be  
13 determined in a well-known manner from a combination of layer composition/stoichiometry,  
14 layer thickness, and/or structural strain induced by adjacent layers. Many material combinations  
15 (extant or hereafter developed), layer thicknesses, and bandgaps may be employed for  
16 modulating many other optical wavelengths without departing from inventive concepts disclosed  
17

1 and/or claimed herein. Several alternative material combinations are disclosed in earlier-cited  
2 application A12 and A20.

3 [0137] An absorption-modulated embodiment of an optical power control device according to  
4 the present invention is shown in Figs. 4A and 4B in which the modulator optical component  
5 comprises an open arcuate modulator optical waveguide 138 positioned axially with respect to  
6 the circumferential-mode optical resonator. Transmission waveguide 110 is shown as a fiber-  
7 optic taper. A fiber-optic waveguide having a saddle-shaped transverse-coupling portion, as  
8 described in detail in earlier-cited application A6, or other fiber-optic waveguide could be  
9 equivalently employed. Circumferential-mode optical resonator 120 is shown as a fiber-ring  
10 resonator as described in detail in earlier-cited application A5 and A15-A18. Other optical  
11 resonator structures could be equivalently employed. In Fig. 4A spacer 139 is shown for  
12 positioning arcuate waveguide 138 at the proper distance from circumferential-mode resonator  
13 120. In this particular embodiment the spacer 139 comprises a portion of an adjacent fiber  
14 segment connected to the fiber-ring resonator with arcuate waveguide 138 deposited thereon,  
15 bonded thereto, or otherwise held in contact therewith. Some experimentation will typically be  
16 required to determine the spacing between circumferential-mode resonator 120 and arcuate  
17 waveguide 138 that produces the desired level of round-trip optical loss for circumferential-  
18 mode resonator 120 and the appropriate modal-index-matching conditions between  
19 circumferential-mode resonator 120 and arcuate waveguide 138. Once the proper thickness of  
20 spacer 139 has been determined, it may be reproducibly fabricated by cleaving, etching,  
21 machining, lithography, cylindrical lithography, or other suitable processing of the adjacent fiber  
22 segment. A functionally equivalent spacer may be employed for other types of optical resonator  
23 as well. The same types of materials used for the absorption-modulated slab and laterally-  
24 confined waveguides described hereinabove may be employed for fabricating absorption-  
25 modulated arcuate waveguide 138. In particular, arcuate waveguide 138 may comprise the  
26 InGaAsP multi-quantum well material described hereinabove, with the alternating quantum well  
27 and barrier layers and surrounding contact layers substantially parallel to circumferential-mode  
28 resonator 120 and with the control electric field applied substantially perpendicular to  
29 circumferential-mode resonator 120. An advantage of this embodiment is increased interaction  
30 length between the circumferential optical mode and the arcuate waveguide relative to the  
31 tangentially positioned waveguides of Figs. 2A, 2B, 3A, and 3B, therefore requiring smaller

1 optical loss per unit distance to achieve the same round trip optical loss in the circumferential-  
2 mode resonator.

3 [0138] A significant property of both tangentially- and axially-positioned absorption-  
4 modulated open modulator optical waveguide structures is that since no re-circulation of any  
5 waveguide optical mode occurs, the presence of the modulator optical waveguide has a  
6 substantially negligible effect on the wavelength-dependent properties and/or resonant behavior  
7 of the adjacent circumferential-mode optical resonator. Such wavelength/frequency shifting  
8 behavior can adversely affect the performance of an optical power control device according to  
9 the present invention, or alternatively may be exploited to enhance said performance, depending  
10 on the design, construction, and use of a particular device.

11 [0139] Various absorption-modulated embodiments of an optical power control device  
12 according to the present invention are shown schematically in Figs. 5A through 5E in which the  
13 modulator optical component comprises a closed optical waveguide (i.e., a modulator optical  
14 resonator 140) positioned tangentially (Figs. 5A and 5B) or axially (Figs. 5C, 5D, and 5E) with  
15 respect to the circumferential-mode resonator 120, and oriented substantially parallel to (Figs.  
16 5A, 5C, and 5D) or substantially perpendicular to (Figs. 5B and 5E) the circumferential-mode  
17 resonator 120. Transmission waveguide 110 is shown (in cross-section) as a tapered fiber-optic  
18 waveguide. A fiber-optic waveguide having a saddle-shaped transverse-coupling portion, as  
19 described in detail in earlier-cited application A6, or other fiber-optic waveguide could be  
20 equivalently employed. Circumferential-mode optical resonator is shown generically as a micro-  
21 disk or micro-ring resonator. Other optical resonator structures, such as the fiber-rings of  
22 earlier-cited application A5 and A15-A18, could be equivalently employed. Absorption-  
23 modulated modulator optical resonator 140 may comprise any of the resonator structures recited  
24 earlier for circumferential-mode resonator 120, including but not limited to spheres, near-  
25 spheres, oblate and/or prolate spheroids, ellipsoids, ovals, ovoids, racetracks, polygons,  
26 polyhedra, cylinders, disks, rings, micro-spheres, micro-disks, micro-rings, fiber-rings, disks  
27 and/or rings on substrates (including structures disclosed in earlier-cited application A12 and  
28 A20), ring or other closed waveguides, and/or functional equivalents thereof, and are shown  
29 generically as micro-disks or micro-rings in Figs. 5A through 5E. Absorption-modulated  
30 modulator optical resonator 140 is shown in Figs. 5A and 5B in substantial tangential  
31 engagement with circumferential-mode optical resonator 120, either in direct mechanical

1 contact, or positioned at a specific distance from the circumferential-mode resonator (by a spacer  
2 or other suitable alignment structure) to yield a desired level of transverse-coupling. An  
3 evanescent portion of the circumferential optical mode extending radially beyond  
4 circumferential-mode resonator 120 may overlap a portion of an optical mode of modulator  
5 optical resonator 140, either a radially-extending portion thereof when substantially parallel to  
6 circumferential-mode resonator 120 (Fig. 5A), or an axially-extending portion thereof when  
7 substantially perpendicular to circumferential-mode resonator 120 (Fig. 5B). Absorption-  
8 modulated modulator optical resonator 140 is shown in Figs. 5C, 5D, and 5E positioned axially  
9 with respect to circumferential-mode optical resonator 120, either in direct mechanical contact,  
10 or positioned at a specific distance from the circumferential-mode resonator (by a spacer or other  
11 suitable alignment structure) to yield a desired level of transverse-coupling. An evanescent  
12 portion of the circumferential optical mode extending axially beyond circumferential-mode  
13 resonator 120 may overlap a portion of modulator optical resonator 140, either an axially-  
14 extending portion thereof when substantially parallel to circumferential-mode resonator 120  
15 (Figs. 5C and 5D), or a radially-extending portion thereof when substantially perpendicular to  
16 circumferential-mode resonator 120 (Fig. 5E).

17 [0140] Absorption-modulated modulator optical resonator 140 may preferably be fabricated  
18 incorporating material having an optical loss (typically optical absorption), at the wavelength of  
19 the circumferential optical mode, that may be controlled by a modulator control component. The  
20 modulator optical resonator 140 should preferably have a resonant optical mode having  
21 substantially the same wavelength as the circumferential optical mode of circumferential-mode  
22 resonator 120 (and hence the optical signal to be controlled). This enables transfer of optical  
23 power from the circumferential-mode resonator and build-up of optical power within the  
24 modulator optical resonator, in turn enabling a relatively small optical loss per unit length in the  
25 modulator optical resonator to produce sufficiently large round trip optical loss for the  
26 circumferential-mode resonator coupled thereto. If the modulator optical resonator and  
27 circumferential-mode optical resonator are not resonant with each other, in contrast, the situation  
28 becomes analogous to that described hereinabove for the open modulator waveguide  
29 embodiments, with relatively large optical loss per unit length required in the modulator optical  
30 resonator to generate sufficient round trip optical loss for the circumferential-mode resonator. A  
31 complication encountered when implementing an embodiment that includes an absorption-

1 modulated modulator resonator arises from the unavoidable wavelength shift of the resonant  
2 optical mode of the modulator resonator that occurs with a change in the optical loss thereof.  
3 The circumferential-mode resonator and modulator optical resonator must be treated as a  
4 coupled-cavity system, and shifts in the modulator resonance wavelength may perturb the  
5 resonances of the coupled system. This effect must be properly accounted for in designing an  
6 optical power control device incorporating a modulator optical resonator, or alternatively, the  
7 effect may be exploited for designing optical power control devices with specific wavelength  
8 dependent performance characteristics. This effect may be somewhat mitigated for an  
9 absorption-modulated resonator modulator component, since the optical loss of such a modulator  
10 resonator tends to reduce the finesse of the modulator resonator and increase the bandwidth of its  
11 resonances, in turn decreasing the effect of the modulator resonances on the circumferential-  
12 mode resonances in the coupled-cavity system. In short, loss- or absorption-modulated resonator  
13 or “closed waveguide” modulator optical components having relatively low finesse ( less than  
14 about 10) may behave substantially less “resonator-like” than the relatively high-finesse  
15 circumferential-mode resonator.

[0141] The optical absorption of modulator optical resonator 140 may be controlled by  
16 electronic, optical, and/or other means in ways completely analogous to those recited for the  
17 modulator waveguides hereinabove, and utilizing the same and/or functionally equivalent  
18 materials for fabrication and the same and/or functionally equivalent modulator control  
19 components. For example, a quantum well, multi-quantum well (MQW), or other semi-  
20 conductor material may be incorporated into the modulator optical resonator as an electro-  
21 absorptive material, wherein the optical absorption may be altered by application of a control  
22 electric field. A modulator control component may comprise control electrodes suitably  
23 positioned to apply the control electric field. Materials described hereinabove (for modulator  
24 waveguides), such as an InGaAsP MQW material controlled by a QCSE, FKE, QCFKE, or  
25 similar mechanism, are also suitable for incorporation into modulator resonator 140. The optical  
26 absorption by such quantum well, MQW, and other semi-conductor materials may alternatively  
27 be controlled by injection of current into the material. The presence of additional charge carriers  
28 (electrons and/or holes, as the case may be) may serve to increase or decrease the optical  
29 absorption of the waveguide material, depending on the bandgap, band structure, and/or doping  
30 of the semiconductor and the wavelength of the optical mode to be modulated. Control  
31

1 electrodes or other electrical contact may serve to inject a control electrical current. Optical  
2 excitation of such materials may also serve to generate carriers, thereby allowing control of the  
3 waveguide optical absorption to be controlled by application of an optical control signal. Other  
4 classes of materials exhibiting photo-bleaching, excited state absorption, saturable absorption,  
5 non-linear optical absorption, and/or resonant non-linear-optical properties may be equivalently  
6 incorporated into the modulator resonator to enable control of the waveguide optical absorption  
7 by application of an optical control signal.

8 [0142] The interaction region (i.e., the volume of overlap between the evanescent portion of  
9 the circumferential optical mode and the modulator optical resonator) is typically limited in  
10 spatial extent by the geometries of the embodiments of Figs. 5A, 5B, 5D, and 5E, limiting the  
11 distance over which modal-index-matching must be controlled. Significantly more stringent  
12 modal-index-matching constraints may arise for the embodiment of Fig. 5C, in which  
13 circumferential-mode resonator 120 and modulator resonator 140 are substantially coaxial, since  
14 the interaction region extends entirely around the circumferential-mode resonator 120. The  
15 entire modulator 140 need not have controlled optical loss. It may be desirable to leave the  
16 interaction region without absorption-controlled material, so that altering the absorption of the  
17 modulator resonator does not affect the modal-index-matching condition in the interaction  
18 region.

19 [0143] For the embodiments of Figs. 5A through 5E, the relative positioning of  
20 circumferential-mode resonator 120 and modulator resonator 140 must be reliable, accurate, and  
21 stable. For a given combination of circumferential-mode resonator (material(s) and/or geometry)  
22 and modulator (material(s) and/or geometry), some experimentation will be necessary to  
23 determine the relative position resulting in the desired degree of transverse-coupling  
24 therebetween (based on the degree of spatial overlap and relative modal-index-matching). Once  
25 the proper relative positioning has been determined, a mechanical spacer or other suitable  
26 alignment aid may be employed to enable reliable, accurate, and stable relative positioning of the  
27 circumferential-mode resonator and the modulator optical resonator in an optical power control  
28 device according to the present invention. Such spacers may comprise a member integrally formed  
29 with the circumferential-mode resonator, a member integrally formed with the modulator  
30 optical resonator, or an independent member fabricated independently of either resonator.

1      Economies of fabrication and/or assembly of the optical control device may be realized when the  
2      spacer is integrally formed with one or the other of these resonators.

3      [0144] Figs. 6A, 6B, and 6C show a resonant optical modulator wherein: transmission optical  
4      waveguide 110 comprises a fiber-optic taper (another type of fiber-optic waveguide, including a  
5      fiber-optic waveguide having a saddle-shaped coupling surface, could be equivalently  
6      employed); circumferential-mode optical resonator 120 comprises a fiber-ring resonator; and  
7      modulator resonator 140 comprises a ring of MQW material (as described above or otherwise)  
8      deposited on, bonded to, or otherwise held in contact with an adjacent fiber segment 141  
9      connected to the fiber-ring. This embodiment corresponds to the arrangement shown  
10     schematically in Fig. 5C. The adjacent fiber segment 141 serves as a mechanical spacer for  
11     reliable, accurate, and stable positioning of modulator resonator 140 relative to the fiber-ring.  
12     Once the proper thickness of the spacer (i.e., adjacent fiber segment 141) has been determined, it  
13     may be reproducibly fabricated by cleaving, etching, machining, lithography, cylindrical  
14     lithography, and/or other suitable processing of the adjacent fiber segment. Layers 172 and 174  
15     may comprise contact layers and/or electrodes for applying a control electric field to a modulator  
16     resonator 140 comprising an electro-absorptive material as enumerated and disclosed  
17     hereinabove. Fig. 7 shows a similar embodiment in which the fiber-ring is fabricated from  
18     PANDA-type polarization preserving optical fiber. One or more internal structural elements 142  
19     of the PANDA fiber, protruding axially from fiber-ring circumferential-mode resonator 120,  
20     serve as the spacer for maintaining reliable, reproducible, and stable relative positioning of the  
21     fiber-ring circumferential-mode resonator and modulator resonator 140 (a micro-disk in this  
22     example, which may include contact/electrode layers not shown). Modulator resonator 140 may  
23     be bonded to or otherwise held in contact with structural elements 142. Structural elements 142  
24     may preferably be left protruding from the fiber-ring by differential etching of the fiber-ring and  
25     the structural elements, or may result from any suitable machining, lithographic, or other  
26     processing technique for producing such structures.

27      [0145] A more elaborate embodiment of an optical power control device according to the  
28      present invention is shown in Figs. 8A and 8B. Fiber-optic waveguide 110 comprises a fiber-  
29      optic taper (another type of fiber-optic waveguide, including a fiber-optic waveguide having a  
30      saddle-shaped coupling surface, could be equivalently employed). Circumferential-mode optical  
31      resonator 120 comprises a fiber-ring resonator. Modulator optical component 140 is fabricated

1 on a semi-conductor substrate and comprises a disk incorporating MQW material, and in this  
2 case may have a relatively low Q-factor (i.e., less resonator-like). Modulator optical component  
3 140 nevertheless may provide a controlled level of optical loss for fiber-ring resonator around  
4 substantially the entire circumference of the fiber-ring resonator, enabling substantially full  
5 modulation of optical power transmitted through fiber taper 110 through relatively small changes  
6 in the absorption per unit length of modulator optical component 140. For wavelengths in the  
7 1.2  $\mu\text{m}$  to 1.7  $\mu\text{m}$  range, a preferred substrate material is InP, while a preferred MQW material is  
8 an InGaAsP MQW layer 147 surrounded by delta-doped InGaAs contact layers 148 and 149,  
9 which enable application of control voltages via bottom electrode 178 (via delta-doped InGaAs  
10 layer 177 and doped InP spacer 179) and top ring electrode 176. An insulating layer 175 may  
11 also be provided. These materials have been described in detail hereinabove, and other suitable  
12 substrate and resonator materials may be equivalently employed. By depositing an appropriate  
13 sequence of epitaxial layers and suitably processing, modulator optical resonator 140 and  
14 associated control electrodes 176 and 178 may be fabricated on substrate 144, which may also  
15 include a central spacer 146. The height of spacer 146 may be controlled to nanometer precision  
16 through standard epitaxial growth techniques, and the fiber-ring resonator may be bonded to or  
17 otherwise held in contact with spacer 146 to achieve reliable, accurate, and stable relative  
18 positioning of modulator optical resonator 140 and circumferential-mode fiber-ring resonator  
19 120.

20 [0146] In a second group of embodiments of the present invention, a level of optical power  
21 transfer from the circumferential optical mode to the modulator optical component 130 (through  
22 transverse-coupling) is controlled by modulating the relative modal-index-matching of the  
23 circumferential optical mode and a modulator optical mode in the interaction region thereof. The  
24 modulator optical component 130 in these so-called “index-modulated” embodiments may  
25 comprise an open optical waveguide structure (in which an optical mode of the waveguide does  
26 not follow a closed path, re-circulate, or resonate within the waveguide; referred to hereinafter as  
27 a “modulator waveguide”), or may comprise a ring, resonator, or other closed optical waveguide  
28 structure (in which an optical mode of the waveguide may re-circulate and/or resonate; referred  
29 to collectively hereinafter as a “modulator resonator”). These modulator components may be  
30 either low-finesse (less than about 10; less “resonator-like”) or high-finesse (greater than about  
31 10; more “resonator-like”), depending on the particular device configuration employed. In either

1 case, the modulator optical component 130 is positioned so that an evanescent portion of the  
2 circumferential optical mode at least partially spatially overlaps a modulator optical mode whose  
3 modal index may be controlled, thereby enabling control of optical power transfer via  
4 transverse-coupling (by control of modal-index-matching) between the circumferential-mode  
5 resonator 120 and the modulator waveguide 130. This in turn controls the round trip optical loss  
6 experienced by the circumferential optical mode in the circumferential-mode resonator 120,  
7 thereby enabling the desired goal of controlled modulation of transmission of the optical signal  
8 through the transmission waveguide 110.

9 [0147] In a third group of embodiments of the present invention, a modulator optical  
10 component 130 may comprise a modulator optical resonator for supporting a modulator optical  
11 mode whose modal index may be controlled, thereby also shifting a resonance wavelength  
12 thereof. In such “resonance-modulated” embodiments, optical power transfer (through  
13 transverse-coupling) from the circumferential optical mode to a modulator optical mode is  
14 controlled by shifting the modulator optical mode into and/or out of resonance with the  
15 circumferential optical mode. This in turn controls the round trip optical loss experienced by the  
16 circumferential optical mode in the circumferential-mode resonator 120, thereby enabling the  
17 desired goal of controlled modulation of transmission of the optical signal through the  
18 transmission waveguide 110.

19 [0148] In a fourth group of embodiments of the present invention, a modulator optical  
20 component 130 may comprise a modulator optical waveguide or resonator, transverse-coupled to  
21 the circumferential-mode optical resonator 120 at two separate points, for supporting a  
22 modulator optical mode whose modal index between the two points may be controlled. In such  
23 “interference-modulated” embodiments, net optical power transfer (through transverse-coupling)  
24 from the circumferential optical mode to a modulator optical mode is controlled by controlling  
25 the relative phase of the modulator optical mode and the circumferential optical mode at the  
26 second coupling region. This in turn controls the round trip optical loss experienced by the  
27 circumferential optical mode in the circumferential-mode resonator 120, thereby enabling the  
28 desired goal of controlled modulation of transmission of the optical signal through the  
29 transmission waveguide 110.

1 [0149] A property common to each of the second, third, and fourth groups of embodiments is  
2 control of the modal index of a modulator optical mode in response to an applied control signal.  
3 This may be preferably achieved by use of a modulator waveguide or resonator fabricated  
4 incorporating an electro-refractive material, an electro-optic material and/or a non-linear optical  
5 material, thereby enabling control of the modal index through application of an electronic and/or  
6 optical control signal.

7 [0150] Examples of suitable electro-optic materials (typically non-centrosymmetric) include,  
8 but are not limited to: semiconductor materials, including zincblende semiconductors; quantum  
9 well materials; multi-quantum well (MQW) materials, including materials exhibiting the  
10 quantum confined Stark effect (QCSE), Franz-Keldysh effect (FKE), quantum-confined Franz  
11 Keldysh effect (QCFKE), or similar mechanism; crystalline oxide electro-optic materials such as  
12 lithium niobate (LNB), potassium niobate (KNB), potassium dihydrogen phosphate (KDP), and  
13 so forth; organic and/or polymeric electro-optic materials, including poled chromophore-  
14 containing polymers; liquid crystals; hybrid multi-layer materials including an electro-optic  
15 and/or non-linear-optic layer in contact with or incorporated within a multi-layer reflector stack  
16 for supporting surface-guided optical modes (SGOMs) such as surface-guided Bloch modes  
17 (SGBMs), for example; hybrid multi-layer materials including an electro-optic and/or non-  
18 linear-optic layer in contact with, incorporated within, or positioned between a pair of multi-  
19 layer reflector stacks; combinations thereof; and/or functional equivalents thereof. A modulator  
20 control component may comprise control electrodes operatively coupled to the modulator optical  
21 component for enabling control of the modal index of the modulator optical mode in the  
22 modulator optical component by application of an electronic control voltage and/or current to the  
23 electro-optic or electro-refractive material. Optical excitation of some of these materials may  
24 also serve to generate charge carriers, thereby enabling control of the modal index by application  
25 of an optical control signal. Materials exhibiting non-linear optical polarizability, saturable  
26 optical polarizability, non-linear Kerr effect, and/or other non-linear optical responses may be  
27 incorporated into the modulator optical component to enable control of the modal index thereof  
28 by application of an optical control signal.

29 [0151] Index-modulated embodiments of an optical power control device according to the  
30 present invention are shown in Figs. 2A, 2B, 3A, and 3B in which the modulator optical  
31 component comprises an open modulator optical waveguide positioned tangentially with respect

1 to the circumferential-mode optical resonator. Transmission waveguide 110 is shown as a fiber-  
2 optic taper. A fiber-optic waveguide having a saddle-shaped transverse-coupling portion, as  
3 described in detail in earlier-cited application A6, or other fiber-optic waveguide could be  
4 equivalently employed. Circumferential-mode optical resonator 120 is shown as a fiber-ring  
5 resonator as described in detail in earlier-cited application A5 and A15-A18. Other  
6 circumferential-mode resonator structures could be equivalently employed. In Figs. 2A and 2B,  
7 the modulator optical component is a slab waveguide 132 in substantial tangential engagement  
8 with circumferential-mode resonator 120, either in direct mechanical contact, or positioned at a  
9 specific distance from the circumferential-mode resonator to yield a desired level of transverse-  
10 coupling.

11 [0152] An evanescent portion of the circumferential optical mode supported by  
12 circumferential-mode resonator 120 may extend radially beyond the circumference thereof, and  
13 may therefore spatially overlap a portion of the slab waveguide 132. Index-modulated slab  
14 waveguide 132 may preferably be fabricated incorporating an electro-optic or electro-refractive  
15 material, so that the modal index of a modulator optical mode may be controlled by a modulator  
16 control component. Alternatively, a nonlinear-optic material may be employed for controlling  
17 the modulator modal index using an optical control signal. The electro-optic or non-linear-optic  
18 material need only be present in the interaction region (i.e., the volume of overlap between the  
19 evanescent portion of the circumferential optical mode and the slab waveguide) which is  
20 typically limited in spatial extent by the size and curvature of circumferential-mode resonator  
21 120, although these materials may also be present elsewhere in the waveguide. The modal index  
22 shift in response to a control signal may preferably be sufficiently large to enable the  
23 circumferential-mode resonator round trip optical loss (due to transverse-coupling into the  
24 modulator waveguide) to reach a level comparable to the optical coupling between the  
25 transmission waveguide 110 and the resonator 120 (i.e., to achieve critical coupling; typically  
26 loss on the order of about 0.5% to about 5% per round trip is needed to yield linewidths  
27 consistent with typical WDM, TDM, or other optical data transmission systems; typically on the  
28 order of 1-40 GHz), or alternatively, to enable the circumferential-mode resonator round trip loss  
29 to exceed critical coupling. The slab waveguide should be kept thin (comparable to the radial  
30 extent of the evanescent portion of the circumferential optical mode beyond the circumference of  
31 resonator 120) and the index of refraction of any substantially homogeneous medium in contact

1 with the face of the slab opposite the circumferential-mode resonator (i.e., a substrate or cladding  
2 layer) must be less than the refractive index of the slab waveguide and no greater than the  
3 refractive index of the circumferential-mode resonator. In this way optical power is confined  
4 within waveguide 132 near resonator 110, thereby substantially eliminating undesired optical  
5 loss. Otherwise optical power coupled from the circumferential-mode resonator 120 into slab  
6 waveguide 132 could propagate away from resonator 110 and be lost.

7 [0153] Modal index mismatch (i.e., phase mismatch) between the circumferential optical mode  
8 and the slab waveguide must be carefully controlled so that, by switching the slab waveguide  
9 modal index between two operational levels, the round trip optical loss of the circumferential-  
10 mode optical resonator (due to coupling of optical power into the modulator waveguide and  
11 dissipation therefrom) may be switched between under- and critically-coupled conditions, or  
12 between critically- and over-coupled conditions. For example, the slab waveguide material  
13 might be chosen to yield a relatively large modal-index-mismatch, thereby limiting the transfer  
14 of optical power to the slab (beat length short compared to interacting propagation distance) and  
15 resulting in over-coupling, while the application of a control signal may change the modal index  
16 so as to reduce the modal-index-mismatch (thereby lengthening the beat length) and thereby  
17 increase transfer of optical power to the slab to a sufficiently high level to result in critical-  
18 coupling and near-zero transmission of the optical signal through the transmission optical  
19 waveguide. In a second example, the slab and circumferential-mode resonator might be well  
20 modal-index-matched and the coupling chosen to yield a critical-coupling condition (interaction  
21 length about one-half the beat length), while the modal index of the slab may be switched to a  
22 level that results in modal-index-mismatch (interaction length roughly equal to the beat length)  
23 and an over-coupled condition. Many other schemes and combinations of modal index  
24 operational levels and modal-index-match/mismatch between the circumferential-mode resonator  
25 and the slab waveguide may be employed while remaining within the scope of inventive  
26 concepts disclosed and/or claimed herein. For a given circumferential-mode optical resonator  
27 geometry, slab waveguide material, and so forth, some experimentation is typically required to  
28 determine the level of transverse-coupling, and the appropriate operational levels of slab  
29 waveguide modal index to produce the desired modulation of the circumferential-mode resonator  
30 round trip loss.

1 [0154] Dissipation of optical power from the modulator waveguide may be achieved in a  
2 variety of ways. The optical power may be allowed to simply propagate in the modulator  
3 waveguide away from the interaction region to radiate into the environment, without an  
4 opportunity to couple back into the circumferential-mode resonator. Alternatively, the  
5 modulator waveguide may be provided with a region of high optical loss (which need not be  
6 modulated). The high-loss region may encompass all or a portion of the modulator waveguide,  
7 and may or may not be spatially separate from the interaction region. The optical loss may be  
8 provided in myriad functionally equivalent ways, including but not limited to optical absorption  
9 and optical scattering, and optical power coupled into the modulator waveguide from the  
10 circumferential-mode resonator may propagate in the region of high optical loss and be absorbed  
11 or otherwise dissipated. Any functionally equivalent means for dissipating optical power  
12 transferred into the modulator waveguide from the circumferential-mode optical resonator may  
13 be employed without departing from inventive concepts disclosed and/or claimed herein.

14 [0155] In Figs. 3A and 3B, the modulator optical component is an index-modulated laterally-  
15 confined waveguide 134 on a substrate 136 and positioned tangentially with respect to  
16 circumferential-mode optical resonator 120 (in this example a fiber-ring circumferential-mode  
17 resonator as described in earlier cited application A5 and A15-A18; other circumferential-mode  
18 structures may be equivalently employed). Most of the same considerations applicable to the  
19 index-modulated slab waveguide embodiment of Figs. 2A and 2B apply to the laterally-confined  
20 waveguide embodiment of Figs. 3A and 3B. The laterally-confined waveguide 134 may  
21 preferably be fabricated incorporating an electro-optic, electro-refractive material, and/or non-  
22 linear-optical material so that the modal index of a modulator optical mode may be controlled by  
23 a modulator control component (by applying an electronic and/or optical control signal), and  
24 which may produce circumferential-mode resonator round trip loss sufficient to achieve critical  
25 coupling. Modal index mismatch between the laterally-confined waveguide and the  
26 circumferential-mode optical resonator must be controlled in the manner described hereinabove  
27 for the index-modulated slab waveguide. In addition to the laterally-confined waveguide  
28 material and the substrate material, the transverse geometry of the laterally-confined waveguide  
29 must also be chosen to yield the desired spatial overlap and modal-index-match/mismatch  
30 properties.

1 [0156] The modal index of index-modulated slab waveguide 132 or laterally-confined  
2 waveguide 134 may be controlled by electronic, optical, and/or other means. For example, a  
3 quantum well, multi-quantum well (MQW), other semi-conductor, or any other suitable electro-  
4 optic material may be incorporated into the modulator waveguide as an electro-optic material, so  
5 that the modal index of the modulator waveguide may be altered by application of a control  
6 electric field. For wavelengths between about 1.2  $\mu\text{m}$  and 1.7  $\mu\text{m}$ , the InGaAsP MQW material  
7 described in detail hereinabove may be used as a suitable electro-optic material, with the modal  
8 index shifted by application of a control electric field through QCSE, FKE, QCFKE, or other  
9 similar mechanism. The properties of the MQW material must differ slightly depending on  
10 whether the material is to be used as an electro-absorptive material or an electro-  
11 refractive/electro-optic material. In both cases the bandgap of the barrier layers should  
12 preferably be substantially greater than the photon energy of the light to be modulated. For an  
13 electro-optic material, however, the quantum well bandgap should be between about 30 meV and  
14 about 60 meV above the photon energy (in contrast to 10-30 meV for an electro-absorptive  
15 material), so that the modulator waveguide does not introduce unwanted optical loss. A  
16 modulator control component may comprise control electrodes suitably positioned to apply the  
17 control electric field. Alternatively, the modal index of such materials may be controlled by  
18 injection of current into the material. The presence of additional charge carriers (electrons or  
19 holes, as the case may be) may serve to increase or decrease the modal index of the waveguide  
20 material, depending on the bandgap, band structure, and/or doping of the semiconductor and the  
21 wavelength of the optical mode to be modulated. Control electrodes or other electrical contact  
22 may serve to inject a control electrical current. Optical excitation of such materials may also  
23 serve to generate charge carriers, thereby allowing control of the waveguide modal index to be  
24 controlled by application of an optical control signal. Other classes of materials exhibiting non-  
25 linear optical polarizability, saturable optical polarizability, non-linear Kerr effect, and/or other  
26 non-resonant non-linear-optical responses may be equivalently incorporated into the modulator  
27 waveguide to enable control of the waveguide modal index by application of an optical control  
28 signal. As with the loss-modulated embodiments, many other electro-optic materials, non-linear-  
29 optical materials, and/or material combinations may be employed to implement an index-  
30 modulated embodiment operable at other wavelengths. Several suitable material combinations  
31 are disclosed in earlier-cited applications A12 and A20.

[0157] An index-modulated embodiment of an optical power control device according to the present invention is shown in Figs. 4A and 4B in which the modulator optical component comprises an open arcuate modulator optical waveguide 138 positioned axially with respect to the circumferential-mode optical resonator. Transmission waveguide 110 is shown as a fiber-optic taper. A fiber-optic waveguide having a saddle-shaped transverse-coupling portion, as described in detail in earlier-cited application A6, or other fiber-optic waveguide could be equivalently employed. Circumferential-mode optical resonator 120 is shown as a fiber-ring resonator as described in detail in earlier-cited application A5 and A15-A18. Other circumferential-mode resonator structures could be equivalently employed. In Fig. 4A spacer 139 is shown for positioning arcuate waveguide 138 at the proper distance from circumferential-mode resonator 120. In this particular embodiment the spacer 139 comprises a portion of an adjacent fiber segment connected to the fiber-ring resonator with arcuate waveguide 138 deposited thereon, bonded thereto, or otherwise held in contact therewith. Some experimentation will typically be required to determine the spacing between circumferential-mode resonator 120 and arcuate waveguide 138 that produces the desired level of round-trip optical loss for circumferential-mode resonator 120 and the appropriate modal-index-matching conditions between circumferential-mode resonator 120 and arcuate waveguide 138. Once the proper thickness of spacer 139 has been determined, it may be reproducibly fabricated by cleaving, etching, machining, lithography, cylindrical lithography, or other suitable processing of the adjacent fiber segment. A similar spacer may be employed for other types of circumferential-mode resonator as well. The same types of materials used for the index-modulated slab and 2D waveguides described hereinabove may be employed for fabricating index-modulated arcuate waveguide 138. In particular, arcuate waveguide 138 may comprise the InGaAsP multi-quantum well material described hereinabove, with the alternating quantum well and barrier layers substantially parallel to circumferential-mode resonator 120 and with the control electric field applied substantially perpendicular to circumferential-mode resonator 120. An advantage of this embodiment is increased interaction length between the circumferential optical mode and the arcuate waveguide relative to the tangentially positioned waveguides, therefore requiring smaller modal index shifts to achieve the same changes in power transfer through transverse-coupling to and round trip optical loss from the circumferential-mode resonator.

1 [0158] A significant property of both tangentially- and axially-positioned index-modulated  
2 open modulator optical waveguide structures is that since no re-circulation of any waveguide  
3 optical mode occurs, the presence of the modulator optical waveguide has a substantially  
4 negligible effect on the wavelength-dependent properties and/or resonant behavior of the  
5 adjacent circumferential-mode optical resonator. Such wavelength/frequency shifting behavior  
6 can adversely affect the performance of an optical power control device according to the present  
7 invention, or alternatively may be exploited to enhance said performance, depending on the  
8 design, construction, and use of a particular device.

9 [0159] Various index-modulated embodiments of an optical power control device according to  
10 the present invention are shown schematically in Figs. 5A through 5E in which the modulator  
11 optical component comprises a closed optical waveguide (i.e., a modulator optical resonator 140)  
12 positioned tangentially (Figs. 5A and 5B) or axially (Figs. 5C, 5D, and 5E) with respect to the  
13 circumferential-mode resonator 120, and oriented substantially parallel to (Figs. 5A, 5C, and 5D)  
14 or substantially perpendicular to (Figs. 5B and 5E) the circumferential-mode resonator 120.  
15 Transmission waveguide 110 is shown as a tapered fiber-optic waveguide. A fiber-optic  
16 waveguide having a saddle-shaped transverse-coupling portion, as described in detail in earlier-  
17 cited application A6, or other fiber-optic waveguide could be equivalently employed.  
18 Circumferential-mode optical resonator is shown as a micro-disk or micro-ring resonator. Other  
19 circumferential-mode resonator structures could be equivalently employed. Index-modulated  
20 modulator optical resonator 140 may comprise any of the resonator structures recited earlier for  
21 circumferential-mode resonator 120, including but not limited to spheres, near-spheres, oblate  
22 and/or prolate spheroids, ovals, ovoids, racetracks, ellipsoids, polygons, polyhedra, cylinders,  
23 disks, rings, micro-spheres, micro-disks, micro-rings, fiber-rings, disks and/or rings on substrates  
24 (including structures disclosed in earlier-cited application A12 and A20), ring or other closed  
25 waveguides, and/or functional equivalents thereof, and are shown generically as micro-disks or  
26 micro-rings in Figs. 5A through 5E. Index-modulated modulator optical resonator 140 is shown  
27 in Figs. 5A and 5B in substantial tangential engagement with circumferential-mode optical  
28 resonator 120, either in direct mechanical contact, or positioned at a specific distance from the  
29 circumferential-mode resonator (by a spacer or other suitable alignment structure) to yield a  
30 desired level of transverse-coupling. An evanescent portion of the circumferential optical mode  
31 extending radially beyond circumferential-mode resonator 120 may overlap a portion of

1 modulator optical resonator 140, either a radially-extending portion thereof when substantially  
2 parallel to circumferential-mode resonator 120 (Fig. 5A), or an axially-extending portion thereof  
3 when substantially perpendicular to circumferential-mode resonator 120 (Fig. 5B). Index-  
4 modulated modulator optical resonator 140 is shown in Figs. 5C, 5D, and 5E positioned axially  
5 with respect to circumferential-mode optical resonator 120, either in direct mechanical contact,  
6 or positioned at a specific distance from the circumferential-mode resonator (by a spacer or other  
7 suitable alignment structure) to yield a desired level of transverse-coupling. An evanescent  
8 portion of the circumferential optical mode extending axially beyond circumferential-mode  
9 resonator 120 may overlap a portion of modulator optical resonator 140, either an axially-  
10 extending portion thereof when substantially parallel to circumferential-mode resonator 120  
11 (Figs. 5C and 5D), or a radially-extending portion thereof when substantially perpendicular to  
12 circumferential-mode resonator 120 (Fig. 5E).

[0160] Index-modulated modulator optical resonator 140 may preferably be fabricated  
incorporating a material enabling control of the modal index of a modulator resonator optical  
mode by applying a control signal via a modulator control component. The modulator optical  
resonator 140 should preferably have a resonant optical mode having substantially the same  
wavelength as the circumferential optical mode of circumferential-mode resonator 120 (and  
hence the optical signal to be controlled). This enables transfer of optical power from the  
circumferential-mode resonator and build-up of optical power within the modulator optical  
resonator, in turn enabling dissipation of optical power from modulator resonator 140 to  
produce sufficiently large round trip optical loss for the circumferential-mode resonator 120  
coupled thereto. If the modulator optical resonator and circumferential-mode optical resonator  
are not resonant with each other, in contrast, the modulator resonator would have a negligible  
effect on the round-trip loss of the circumferential-mode resonator. Index-modulated modulator  
optical resonator 140 may preferably be fabricated incorporating an electro-optic or non-linear-  
optical material, so that the modal index of a modulator resonator optical mode may be  
controlled by a modulator control component. A complication encountered when implementing  
an embodiment that includes an index-modulated modulator resonator arises from the  
unavoidable wavelength shift of the resonant optical mode of the modulator resonator that occurs  
with a change in the modal index thereof. The circumferential-mode resonator and modulator  
optical resonator must be treated as a coupled-cavity system, and shifts in the modulator

1 resonance wavelength may perturb the resonances of the coupled system. This effect must be  
2 properly accounted for in designing an optical power control device incorporating a modulator  
3 optical resonator, or alternatively, the effect may be exploited for designing optical power  
4 control devices with specific wavelength dependent performance characteristics. One approach  
5 might involve providing the modulator resonator with two index-modulated regions: one at the  
6 interaction region near the circumferential-mode resonator and another far from the  
7 circumferential-mode resonator. Application of a control signal may serve to change the modal  
8 index in the interaction region to change the level of optical power transfer by transverse-  
9 coupling, while the modal index in the second region may change by an appropriate amount to  
10 leave the resonance frequency of the modulator resonator substantially unchanged. The effects  
11 of shifting resonances in the coupled-cavity system may be somewhat mitigated for a low-Q  
12 index-modulated resonator modulator component, since the dissipation of optical power from the  
13 modulator resonator tends increase the bandwidth of its resonances, in turn decreasing the effect  
14 of the modulator resonances on the circumferential-mode resonances in the coupled-cavity  
15 system. In short, index- or coupling-modulated resonators or “closed waveguide” modulator  
16 optical components having relatively low finesse (less than about 10) may behave substantially  
17 less “resonator-like” than the relatively high-finesse circumferential-mode resonator.

[0161] Alternatively, the modulator optical resonator 140 may be a relatively high-Q resonator  
18 and should preferably have a resonant optical mode having substantially the same wavelength as  
19 the circumferential optical mode of circumferential-mode resonator 120 (and hence the optical  
20 signal to be controlled). Transfer of optical power from the circumferential optical mode of  
21 circumferential-mode resonator 120 into modulator optical resonator 140, and subsequent  
22 dissipation of optical power therefrom, may be modulated (to a degree sufficient to switch the  
23 optical power control device between conditions of under- and critical-coupling, or between  
24 conditions of critical- and over-coupling) by modulation of the modal index of the modulator  
25 resonator 140 to shift the resonance wavelength thereof from a condition of resonance with the  
26 circumferential optical mode (yielding greater optical power transfer to the modulator optical  
27 mode) to a condition of non-resonance with the circumferential optical mode (yielding little or  
28 no optical power transfer to the modulator optical mode). Dissipation of optical power from the  
29 modulator resonator 140 in such a “resonance-modulated” device may be achieved in a variety  
30 of ways. The dissipated optical power may be allowed to simply propagate in the modulator  
31

1 resonator away from the interaction region to radiate into the environment, without an  
2 opportunity to couple back into the circumferential-mode resonator. Alternatively, the  
3 modulator resonator may be provided with a region of high optical loss (which need not be  
4 modulated). The high-loss region may encompass all or a portion of the modulator resonator,  
5 and may or may not be spatially separate from the interaction region. The optical loss may be  
6 provided in myriad functionally equivalent ways, including but not limited to optical absorption  
7 and optical scattering, and optical power coupled into the modulator resonator from the  
8 circumferential-mode resonator may propagate in the region of high optical loss and be absorbed  
9 or otherwise dissipated. Any functionally equivalent means for dissipating optical power  
10 transferred into the modulator resonator from the circumferential-mode optical resonator may be  
11 employed without departing from inventive concepts disclosed and/or claimed herein.

[0162] Any of the electro-optic or non-linear-optical materials recited hereinabove for an index-modulated modulator waveguide, or functional equivalents thereof, may be incorporated into a modulator resonator according to the present invention, with suitable adjustment to yield electro-refractive behavior instead of electro-absorptive behavior. An index- or resonance-modulated modulator optical resonator may be positioned relative to a circumferential-mode fiber-ring resonator by a spacer as shown in Figs. 6A-6C, Fig. 7, and Figs. 8A-8B.

[0163] A preferred material for any of the index-modulated modulator optical waveguides and/or resonators of Figs. 3A-3B, 4A-4B, 5B-5D, 6A-6B, and/or Fig. 7 may be a multi-layer reflector stack (for example, a distributed Bragg reflector, or DBR, stack). Such multi-layer reflector stacks may be employed to support and/or guide propagation of so-called surface guided optical modes (SGOMs) such as surface-guided Bloch modes (SGBMs), for example. A SGOM supported by any of the index-modulated modulator waveguides and/or modulator resonators of Figs. 3A-3B, 4A-4B, 5B-5D, 6A-6B, and/or Fig. 7 (fabricated as a multi-layer-reflector stack) may serve as the modulator optical mode. The surface-guided modulator optical mode may be transverse-coupled to the circumferential optical mode from the top of the stack (referred to as “surface-coupled”), or from the side of the stack (referred to as “side-coupled”). The multi-layer-reflector stack is preferably fabricated (typically using epitaxial, evaporative, effusive, and/or chemical vapor deposition/growth techniques, wafer-bonding techniques, lithography, spatially-selective processing, and/or other related techniques) incorporating one or more electro-optic layers and control electrodes for applying a control electric field to control the

1 material index of the electro-optic layer. Alternatively, the multi-layer reflector may include one  
2 or more non-linear-optical layers controlled by an optical signal. The strongly dispersive optical  
3 properties of a multi-layer-reflector-guided SGOM (a substantially flat dispersion relation in the  
4 operating wavelength range, so that a narrow range of wavelengths cover a wide range of  
5 propagation constants or modal indices) serve to produce a substantially larger modal index shift  
6 of the SGOM for a given applied control voltage level than previous electro-optic devices. This  
7 in turn enables optical power control devices incorporating electro-optic or non-linear-optical  
8 multi-layer-reflector waveguides or resonators according to the present invention to be operated  
9 with substantially smaller control voltages (and lower electrical drive power consumption) or  
10 lower-intensity optical signals than their counterparts incorporating simpler materials and/or  
11 geometries. A wide variety of material combinations, layer sequences, and/or  
12 fabrication/processing techniques may be employed to implement an electro-optic/DBR stack  
13 embodiment of the present invention. Many examples of such surface-guiding multi-layer  
14 refelctor stack waveguides and/or resonators are disclosed in earlier-cited applications A12 and  
15 A20, and any of those examples may be employed in an index-modulated modulator, and/or a  
16 resonance-modulated modulator resonator, without departing from inventive concepts disclosed  
17 and/or claimed herein.

[0164] In an alternative embodiment of any of the index-modulated modulator optical  
1 waveguides and/or resonators of Figs. 3A-3B, 5A, and/or 5E, a pair of multi-layer reflector  
2 stacks may be employed surrounding a core layer; the multi-layer-reflector stacks may be similar  
3 to or may differ from one another. In such structures the modulator optical mode may be  
4 supported and substantially confined by the multi-layer-reflector stacks in a region near the core  
5 layer. The confined modulator optical mode may be transverse-coupled to the circumferential  
6 optical mode from the top or side of the multi-layer stack (surface-coupled or side-coupled). The  
7 stack is preferably fabricated (typically using epitaxial, evaporative, effusive, and/or chemical  
8 vapor deposition/growth techniques, wafer-bonding techniques, lithography, spatially-selective  
9 processing, and/or other related techniques) incorporating one or more electro-optic layers with  
10 control electrodes for applying a control electric field to control the material index of the electro-  
11 optic layer. Alternatively, the stack may incorporate one or more non-linear-optical layers  
12 controlled by an optical signal. The strongly dispersive optical properties of a dual-refelctor-  
13 guided confined optical mode enable operation of devices with substantially smaller control

1 voltages (and lower electrical drive power consumption) or lower-intensity optical signals than  
2 their counterparts incorporating simpler materials and/or geometries, in a manner analogous to  
3 that described hereinabove for SGOMs. Many examples of such dual-multi-layer-reflector stack  
4 waveguides and/or resonators are disclosed in earlier-cited application A12 and A20, and any of  
5 those examples may be employed in an index-modulated modulator, and/or a resonance-  
6 modulated modulator resonator, without departing from inventive concepts disclosed and/or  
7 claimed herein.

8 [0165] Exemplary fabrication procedures and cross-sectional structures of index-modulated  
9 electro-optic/Bragg stack waveguides or resonators are depicted in Figs. 9 through 16. The  
10 flowchart of Fig. 9 and process diagram of Fig. 10 illustrate fabrication (by epitaxial techniques  
11 and/or other functionally equivalent deposition/growth/processing techniques) of a multi-layer  
12 reflector stack 2202 and a high-index core layer 2204 on a first substrate 2210, the reflector stack  
13 comprising alternating  $\lambda/4$  (quarter-wave) layers of materials differing in material refractive  
14 index (i.e., a distributed Bragg reflector in this example). A preferred reflector stack may  
15 comprise alternating  $\lambda/4$  layers of GaAs (index about 3.5) and high-aluminum-fraction AlGaAs  
16 (between about 0.90 and about 0.97 aluminum; index about 3.2) on a GaAs substrate. In general  
17 the appropriate quarter-wave thickness is determined based on the index of the material  
18 ultimately present in a given layer; this may not be the same material initially deposited if  
19 subsequent processing (oxidation, for example) brings about a chemical conversion of the layer  
20 to a new material. A doped layer 2220 of InGaAs may be provided between the substrate 2210  
21 and the reflector stack 2202 to enable subsequent electrical contact for applying the control  
22 voltage, and a GaAs or AlGaAs cladding layer may be provided on top of the Bragg stack if  
23 desired.

24 [0166] On a second substrate 2240, a MQW material electro-optic layer 2208 may be  
25 fabricated (for example, the InGaAsP MQW material as described hereinabove for use as an  
26 electro-absorptive or electro-optic material for wavelengths from about 1.2  $\mu\text{m}$  to about 1.7  $\mu\text{m}$ ;  
27 other functionally equivalent electro-optic materials may be used, or a non-linear optical material  
28 may be employed) and may include cladding layers above and below the MQW layers (if  
29 desired) and a doped layer 2230 between the MQW layer 2208 and the substrate 2240 to enable  
30 subsequent electrical contact for applying the control voltage. The top of the MQW material  
31 2208 (or the top cladding layer, if present) is then wafer-bonded or equivalently secured to the

1 high-index core layer 2204 (or top cladding layer, if present) on the reflector stack 2202. The  
2 MQW substrate 2240 may then be etched away or otherwise equivalently removed, leaving the  
3 MQW electro-optic layer 2208, contact layer 2230, and bottom cladding layer (if present)  
4 exposed and accessible for subsequent transverse optical surface coupling to the circumferential-  
5 mode optical resonator. Use of wafer-bonding techniques in this example is required due to the  
6 lattice mismatch between the GaAs/AlGaAs reflector stack and the InGaAsP MQW. If lattice-  
7 compatible materials are employed for the reflector stack and the electro-optic layer, then both  
8 may be deposited sequentially on a single substrate, and no wafer-bonding step is required.  
9 Numerous examples of multi-layer reflector and electro-optic/non-linear-optic material  
10 combinations, some requiring wafer-bonding and others fabricated on a single substrate, are  
11 disclosed in earlier-cited applications A12 and A20.

[0167] The wafer-bonded reflector stack/MQW composite structure 2250 may then be  
spatially-selectively etched (using etch mask 2270, for example) and/or otherwise processed to  
leave a protruding ridge structure of the appropriate shape (a straight or arcuate segment 2252  
for an open waveguide as in Fig. 11; a ring, racetrack, or other closed path for a closed  
waveguide or resonator 2254 as in Fig. 12) on substrate 2210. The protruding ridge structure  
provides lateral confinement for the waveguide/resonator structure. As shown in cross-section in  
Figs. 13 and 14, ridge structure 4300 may be oxidized, converting lateral portions 4332 of each  
AlGaAs layer 4330 to aluminum oxide and leaving a central portion 4334 of AlGaAs in each of  
the AlGaAs layers 4330. These central AlGaAs portions 4334 together with GaAs layers 4320  
form a core of the waveguide (or resonator) structure 4300, while the lateral aluminum oxide  
portions 4332 together form lateral cladding layers of the waveguide (or resonator) structure  
4300. The aluminum fraction of each of the AlGaAs layers may be the same, yielding a  
waveguide (or resonator) core of substantially uniform width upon lateral oxidation (Fig. 13), or  
the aluminum fraction may decrease from the bottom of the reflector stack near the substrate up  
towards the top of the stack, yielding a waveguide (or resonator) core that is narrower at the  
bottom of the Bragg stack near the substrate and that becomes wider toward the top of the stack  
upon lateral oxidation (Fig. 14). Oxidation proceeds more rapidly with increasing Al content of  
a given layer. Other processing techniques may be employed to yield alternative laterally-  
confined waveguide/ resonator structures while remaining within the scope of inventive concepts

1 disclosed and/or claimed herein, and many of these are disclosed in earlier-cited applications  
2 A12 and A20.

3 [0168] The MQW material may act as an electro-optic spacer on the reflector stack waveguide  
4 (or resonator), and application of the control voltage across the doped contact layers changes the  
5 material index of the MQW. This in turn results in substantially larger changes in the modal  
6 index of the SGOM supported by the reflector stack, and therefore substantial shifts in the  
7 modal-index-matching condition (and degree of optical power transfer between under-, critical-,  
8 and/or over-coupling) between the reflector stack and the circumferential-mode resonator.

9 Larger changes in the level of optical power transfer may be achieved for a given applied control  
10 voltage using an electro-optic/reflector stack device than by using a simple electro-optic device  
11 as described earlier herein, enabling substantial reduction of control voltage and electrical drive  
12 power to operate an optical power control device. Similar reductions in optical control signal  
13 intensity result from use of non-linear-optic/reflector stack devices. While multi-layer reflector  
14 stacks fabricated from GaAs/AlGaAs are currently preferred (since they are already well-  
15 understood and well-characterized and yield high-index-contrast reflector structures), other  
16 combinations of materials yielding functionally equivalent Bragg stacks (currently known or  
17 hereafter developed) may be employed without departing from inventive concepts disclosed  
18 and/or claimed herein. Similarly, while InGaAsP multi-quantum well materials are currently  
19 preferred (since they are already well-understood and well-characterized, and are suitable for use  
20 in the technologically important 1.2-1.7  $\mu\text{m}$  wavelength range), other multi-quantum well  
21 materials yielding functionally equivalent electro-optic, electro-absorptive, and/or non-linear-  
22 optical properties (currently known or hereafter developed) may be employed without departing  
23 from inventive concepts disclosed and/or claimed herein. Alternatively, any of the electro-optic,  
24 electro-absorptive, and/or non-linear-optic materials disclosed hereinabove may be equivalently  
25 employed for fabricating a waveguide/resonator in conjunction with a multi-layer reflector stack  
26 as disclosed herein.

27 [0169] The flowchart of Fig. 15 and the fabrication process diagram of Fig. 16 illustrate  
28 fabrication (by epitaxial and/or other functionally equivalent growth/deposition/processing  
29 techniques) of a multi-layer reflector stack 2002 and high-index core layer 2004 on a substrate  
30 2010. At least one layer of the reflector stack 2002 is an electro-optic or non-linear-optical  
31 material layer. An exemplary electro-optic Bragg stack of this type may comprise alternating

1    $\lambda/4$  layers of high-aluminum-fraction AlGaAs and GaAs/InGaAs MQW material on a GaAs  
2   substrate, and may include top and bottom doped InGaAs contact layers 2020 and 2030 and a top  
3   GaAs cladding layer. The Bragg stack 2002 is processed (by lithography or other functionally  
4   equivalent technique) to form a ridge structure and laterally oxidized as described hereinabove,  
5   yielding a central core and lateral cladding for the waveguide (or resonator) structure, which may  
6   be surface-transverse-coupled to the circumferential-mode optical resonator. Application of a  
7   control voltage across the contact layers 2020 and 2030 results in a shift of the material index of  
8   the GaAs/InGaAs MQW material, substantially larger shifts in the modal index of the SGOM,  
9   and substantial shifts in the modal-index-matching condition (and degree of optical power  
10   transfer between under-, critical-, and/or over-coupling) between the Bragg stack waveguide and  
11   the circumferential-mode resonator. GaAs/InGaAs MQW material is not ideally suited for  
12   modulating optical wavelengths typically used in long-haul fiber-optic telecommunications  
13   (between about 1.2 mm and about 1.7 mm), but rather better suited for the 0.7-0.8  $\mu\text{m}$  region  
14   (often utilized for so-called metro, or short-haul fiber-optic telecommunications networks).  
15   Bragg stacks incorporating any suitable MQW materials or other electro-optic and/or non-linear-  
16   optical materials (including InGaAsP MQW material, suitable for typical fiber-optic  
17   telecommunications wavelengths), currently known or hereafter developed, may be equivalently  
18   employed without departing from inventive concepts disclosed and/or claimed herein. Suitable  
19   combinations of materials will typically be determined by lattice-compatibility, bandgap,  
20   operating wavelength, and so on.

21   **[0170]** Any of the reflector stack structures including electro-absorptive, electro-optic, and/or  
22   non-linear-optical materials as described hereinabove and/or disclosed in earlier-cited  
23   applications A12 and A20 may be used to fabricate a resonance-modulated modulator optical  
24   resonator, wherein the modal index shift of the applied control voltage functions to shift the  
25   resonance wavelength of the modulator optical mode into and out of resonance with the  
26   circumferential optical mode. The shifting of the resonance wavelength of the modulator  
27   resonator serves to switch the level of optical power transfer from the circumferential-mode  
28   resonator between under-, critical-, and/or over-coupling, as described hereinabove.

29   **[0171]** As a further generalization of resonant optical power control devices according to the  
30   present invention, the circumferential-mode resonator may comprise a multi-layer-reflector stack  
31   structure fabricated in a manner analogous to the fabrication procedures described herein and in

1 earlier-cited applications A12 and A20. Such a circumferential-mode optical resonator may  
2 comprise a single-reflector stack structure supporting a surface-guided resonant optical mode,  
3 and transverse-coupling between the circumferential-mode resonator and the transmission  
4 waveguide and between the circumferential-mode resonator and the modulator optical  
5 component may occur through an axially-extending or radially-extending evanescent portion of  
6 the surface-guided optical mode of the circumferential-mode resonator. Alternatively, the  
7 circumferential-mode optical resonator may comprise a dual reflector stack structure  
8 substantially confining a resonant optical mode therebetween, and transverse-coupling between  
9 the circumferential-mode resonator and the transmission waveguide and between the  
10 circumferential-mode resonator and the modulator optical component may occur through an  
11 axially-extending or radially-extending evanescent portion of the confined optical mode of the  
12 circumferential-mode resonator.

[0172] In order to achieve and maintain reliable, accurate, and stable transverse-coupling  
1 between a transmission optical waveguide, a circumferential-mode resonator, and a modulator  
2 optical component during and after manufacture of a resonant optical modulator according to the  
3 present invention, an alignment device may be employed, as illustrated by the exemplary  
4 assemblies of Figs. 17A-17C, 18A-18C, 19A-19B, 20A-20B, 21A-21B, 22A-22B, 23A-23B, and  
5 24A-24B. Such an alignment device may comprise a first alignment substrate 502 having a  
6 transmission-waveguide-alignment groove 506 thereon, and various embodiments are described  
7 in detail in earlier-cited applications A5 and A15-A18. Alignment substrate 502 may be further  
8 provided with a circumferential-mode-resonator-alignment groove 504, or groove 504 may be  
9 provided on a second alignment substrate 702. A method for fabricating a resonant optical  
10 power control device according to the present invention comprises the steps of: 1) positioning  
11 and securing a transmission fiber-optic waveguide within the transmission-waveguide-alignment  
12 groove 506; and 2) positioning and securing the circumferential-mode optical resonator within  
13 the resonator-alignment groove 504 (as shown, for example, in Figs 17A-17C and 18A-18C for  
14 the case when grooves 504 and 506 are both provided on substrate 502). The transmission fiber-  
15 optic- waveguide may comprise a fiber taper 600, an optical fiber 300 with a saddle-shaped  
16 transverse-coupling segment, or any other functionally equivalent transmission optical  
17 waveguide having an transverse-coupling segment. The circumferential-mode resonator may  
18 comprise a microsphere 620 connected to a neck portion 622 of a microsphere fiber segment  
19

1 624, a fiber-ring 602 connected to adjacent fiber segments 604, or any other functionally  
2 equivalent circumferential-mode resonator structure. Notwithstanding the exemplary  
3 combinations shown in the Figures, any suitable circumferential-mode resonator may be  
4 combined with any suitable transmission fiber-optic waveguide to yield a resonant optical power  
5 control device according to the present invention. The transmission-waveguide-alignment  
6 groove 506 may be positioned on the alignment substrate 502, and resonator-alignment groove  
7 504 may be positioned on the alignment substrate 502 or 702, so that when positioned and  
8 secured therein (and substrates 502 and 702 are assembled, if groove 504 is provided on  
9 substrate 702), the transmission fiber-optic waveguide and the circumferential-mode resonator  
10 are in substantial tangential engagement (usually mechanical contact between the waveguide and  
11 the circumference of the resonator), thereby transverse-coupling the circumferential-mode  
12 resonator to the transmission fiber-optic waveguide. Optical coupling between the  
13 circumferential-mode resonator and the transmission fiber-optic waveguide may be achieved as  
14 long as at least portion of an evanescent portion of one of the circumferential optical mode of the  
15 resonator and a propagating optical mode of the transmission fiber-optic waveguide spatially  
16 overlaps at least a portion of the other optical mode. Actual mechanical contact is not required,  
17 only that the resonator and fiber be sufficiently close to permit the overlap. However, in a  
18 preferred embodiment of an optical power control device according to the present invention,  
19 optical coupling between the resonator and the fiber may be most accurately, reliably, and stably  
20 achieved by positioning and securing the circumferential-mode resonator and the transmission  
21 fiber-optic waveguide in mechanical contact with one another.

22 [0173] The second alignment substrate 702 of the alignment device may also have the  
23 modulator optical component secured thereto or mounted thereon. Alignment substrate 702  
24 (and/or alignment substrate 502, if groove 504 is provided thereon) may be suitably  
25 mechanically indexed or otherwise provided with means for reliably, accurately, and stably  
26 positioning the modulator optical component for transverse-coupling to the circumferential-  
27 mode optical resonator (either in direct mechanical contact or a space therebetween). The  
28 alignment grooves 504 and 506, and any indexing or other alignment means, together serve to  
29 suitably position the modulator optical component, circumferential-mode resonator, and  
30 transmission fiber-optic waveguide relative to each other, when all are secured to the assembled  
31 alignment device.

1 [0174] Similar alignment structures may be employed whether the modulator optical  
2 component is a waveguide or resonator, and whether the modulator optical component is loss-  
3 modulated, index-modulated, resonance-modulated, or interference-modulated. Exemplary  
4 assemblies include: slab modulator waveguide 132 shown in Figs. 19A-19B (with groove 504 on  
5 substrate 502); 2D modulator waveguide 134 on substrate 136 shown in Figs. 20A-20B (with  
6 groove 504 on substrate 502); modulator resonator 140 (side-coupled, as in Fig. 5A) shown in  
7 Figs. 21A-21B (with groove 504 on substrate 502); ridge modulator waveguide 2252 (surface-  
8 coupled) shown in Figs. 22A-22B (with groove 504 on substrate 702); ridge modulator  
9 waveguide 2252 (side-coupled) shown in Figs. 23A-23B (with groove 504 on substrate 702); and  
10 ridge modulator resonator 2254 (surface-coupled, as in Fig. 5B) shown in Figs. 24A-24B (with  
11 groove 504 on substrate 702). The embodiment of Figs. 24A-24B may be modified to provide  
12 side-coupling between modulator resonator 2254 and fiber-ring resonator 602 (as in Fig. 5E).

13 [0175] The present invention has been set forth in the forms of its preferred and alternative  
14 embodiments. It is nevertheless intended that modifications to the disclosed resonant optical  
15 modulators and methods of fabrication and use thereof may be made without departing from  
16 inventive concepts disclosed and/or claimed herein.